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The Applied Physicist*

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I

THE physicist has recently become very self-conscious. He feels that he is under inspection by a great many people, and being naturally of a retiring disposition, he is disquieted. I suppose a paramecium feels the same way just before it is about to divide and form two paramecia. Some observers are beginning to fear that we are shortly to have two kinds of physicists, classified with varying degrees of respect as fundamental and applied physicists, as pure and practical physicists, or even as pedants and plumbers.

The paramecium family is still, after millions of years, nothing but a group of non-cooperative unicellular organisms. The egg cell of a mammal also divides periodically, but the new cells stick together and instead of emphasizing their individuality as do those of the protozoa, they collaborate with the result that the congregation of cells becomes a functioning animal with capabilities far greater than the mere sum of the capabilities of its individual parts. The applied physicist must be allowed to develop his cell of self-consciousness in the body of physical science, but he must not be permitted to depart into a unicellular existence, as have so many of the previous cells of physics which have now taken on engineering labels.

Before one can define the term applied physicist one must know what a physicist is. While all physicists would doubtless claim to know what they are, much difference of opinion crops up when borderline cases are considered. If everyone agrees that Einstein is a physicist, plenty of arguments can be started by claiming that Edison was one also.

A committee of a prominent body of physicists is said recently to have bogged down completely in its attempt to define a physicist. A chemist has been defined as one who loves working with substances, and a physicist as one who has

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a passion for precise measurements, yet I have known carpenters who fulfilled both requirements. There are some very fine physicists who have never measured anything precisely, and some very poor ones who spend a great deal of time polishing up an extra decimal place. It would seem that the chief qualification of a physicist is his preoccupation with phenomena which concern the interaction of matter and energy. It may be objected that such a definition is too all-embracing, but such an objection brings us directly to the chief criticism of physicists which is made by engineers, industrialists, and even by their fellow scientists—their impracticality.

It is easy to show that a physicist is impractical only by definition. As the tree of physics has grown it has led to more practical results than any other fundamental science, but every time a branch of this tree has become particularly green in practicality, that branch has been sawed off and deposited in the wood pile of engineering. Then the chemist, for example, climbing around in his scientific tree covered with magnificent branches of practical greenery, points the finger of scorn at the physicist who sits happily contemplative atop the denuded trunk of *his* scientific tree and cries "Impractical!" while those practical physicists who have gone down to work on the wood pile he calls engineers.

There is of course no objection to this, except insofar as there is danger that the branches which have been cut from the tree fail to take root, or that the physicists in the tree-top and those in the wood pile fail to keep interested in each other. I recently noticed an ivy vine clinging to the side of a laboratory building, green and flourishing and quite unaware that a steam shovel had just torn away its roots. There are branches of engineering that are in the position of that ivy vine, and their danger is that the inability to recognize their own withering increases more rapidly than does the withering itself.

II

The new interest in the applied physicist seems to represent an attempt to educate students consciously to help keep closed the gap between fundamental physics and engineering. An engineer is of necessity not only a conservative but an extravert, and it is necessary that the wood pile on which he is perched be of well-seasoned logs. But one limitation of well-seasoned logs is that they seldom grow. The physicist occupied with fundamental research has been accused of being an introvert, and if true this is quite as it should be, for experience has shown that the fundamental research laboratory must of necessity take on something of the aspect of the cloister. Men of the go-getting real-estate agent type, whose latest thought of the night before appears in the morning papers, do their reputations and their science more harm than good, for the simple reason that scientific theory and the interpretation of experiment demand reasoned consideration. Elimination of bias and prejudice does not flourish in the limelight.

In the training of students majoring in physics the newly emphasized category of applied physics is important as indicating a desire on the part of educators to give some of their students less of the stamp of the college professor, and more of that of the research worker. The main duty of the professor of engineering has been to turn out engineers, but the main duty of the professor of physics has not been to turn out physicists. His chief effort has been devoted to giving students in science, engineering, and some of the arts the basic physics training which they need. Only as a side-issue have students been professionally educated in physics, and I believe it is still true that in most colleges there are ten nonmajor students to be taught physics to every one who majors in physics.

III

Until a very few years ago the average physics graduate either wandered off into something unrelated to physics, or found that he was "called" to a career in physics and went on into graduate study and eventually into teaching. The number of physics graduates eventually increased to the point where teaching positions were not available even for all the better graduates, and the overflow has increasingly gone into industrial positions. Then came the plaint from industry that these men tended to be impractical,

and to entertain visions of discovering new laws of nature while they had completely forgotten how to adjust a galvanometer. In my opinion this condition has arisen largely from the fact that most physics departments have turned out physicists only as a by-product.

Employers in industry have great need for men trained in the fundamentals of the interaction of matter and energy. Engineers can only be given a limited training in these fundamentals, for they must also learn how to write clear reports, how to make cost estimates, and how to plan to do a particular job in the cheapest way. They must be able to work from a handbook, and it is impossible for them to keep up with the growth of all sciences fundamental to their field. An electrical engineer who designs high voltage transmission lines must be guided by the previous experience of other engineers, so as not to waste his employer's money. Yet a time sometimes comes when an atom-splitting physicist who has developed a new type of high voltage generator may temporarily be a better guide.

An engineer who keeps looking about him for high-signs from atom-splitters will not get very far. How reasonable, then, to have a class of physicists whose business is to keep watch for such high-signs, and even to make them occur more frequently.

Suppose that an engineer specializes in steam boilers, and it turns out that he needs an extension of the steam tables to carry out his routine calculations. And suppose that to extend the steam tables it would be convenient to know more about the fundamental properties of the water molecule, data which, let us say, can best be obtained by the methods of band spectroscopy. It is ridiculous to expect the engineer to keep up with the progress of band spectroscopy, and it is just as unreasonable to expect the band spectroscopist to be continually aware of all possible needs for his data. We have in the past expected the physical chemist to bring this particular need and its fulfillment together. Yet the term physical chemist, in its orthodox sense, is of course merely another name for a thermodynamic physicist, one of the older castes of applied physicists which became so useful to chemistry that it was absorbed completely into that field.

IV

It is a common experience for an experimental physicist to wish to test a theoretically derived formula in terms of his experimental results, only to find that the theorist has left his equations dangling in such intangible form that the experimenter is at a loss how to interpret them. Here is what one experimental physicist wrote to a theoretical physicist in this regard:*

"There is one thing I would be glad to ask you. When a mathematician engaged in investigating physical actions and results has arrived at his own conclusions, may they not be expressed in common language as fully, clearly, and definitely as in mathematical formulae? If so, would it not be a great boon to such as we to express them so—translating them out of their hieroglyphics that we also might work upon them by experiment?" That his problem is not entirely modern is obvious when we learn that the experimenter who wrote this was Michael Faraday, and the theorist to whom he wrote was Clerk Maxwell.

On the borderlines between neighboring sciences the gap is even greater. A biologist who wants to study the lethal effects of light on bacteria would like to be able to turn his cultures over to a physicist, the latter to shine on the proper cultures a stated number of ergs of monochromatic radiation of wave-lengths specified by the biologist, and then to notify the biologist of the result. In the biologist's mind the provision and measurement of high intensity monochromatic light are merely routine procedures, incidental to his important researches on the effects of light on bacteria. But the poor physicist is plagued with a host of troubles concerning fused quartz prisms and radiation thermopiles, galvanometers which do not respond linearly, and what not, and to him these troubles are what consitute the research, with the final illumination of the cultures only an incidental routine. More usually he says to the biologist, "Here is how I would suggest getting such monochromatic light—now go ahead and carry out your experiments." The result frequently is that the job

*Quoted in Candler's *Atomic Spectra.*

does not get done at all until a biophysicist is hired, and he is only too apt to be looked down upon by both biologist and physicist as a mere technician who understands the subtleties of neither science.

V

One of the great dangers in any applied physics curriculum is that it becomes the haven of less intelligent students fitted only for routine types of work, who, not only lacking interest in fundamental research, but ability for any kind of research, become what have been referred to as doctors of plumbing. The standards of requirement in applied physics should be quite as rigid as those in a general physics curriculum, and they might well, in fact, be made temporarily more rigid during the transition period when such curricula are getting started, to discourage entry by students who have become mired in the general physics curriculum.

Another danger against which the applied physicist must guard is that of getting an inferiority complex relative to the general physicist, just as a few years ago there was a period when the experimental physicist had an inferiority complex toward the theoretical physicist, as the physicist has always had toward the mathematician, and the mathematician toward the philosopher. The physicist has in his turn looked down on the chemist, the chemist on the biologist, thence the contempt descending through the psychologist and ending up in the school of education. It is probable that much of the self-composure of the physicist while enduring accusations of impracticality in the past, has arisen from his internal feeling that, after all, he was a little closer to the real essence of things than his critics! The applied physicist must be prepared to endure these airs on the one side and the criticisms of the ultra-conservative on the other, and to the degree that he is able to adjust himself to these conflicting demands will he contribute to the progress and utilization of science.

VI

A number of educators have expressed the opinion that the preparation for applied physics should be domiciled in the college of engineering. I take such hearty issue with this view as to make me think that by applied physics we mean two different kinds of physics. I would distinguish very carefully between a curriculum in applied physics and a curriculum in engineering physics. Physics is a very important part of the training of the engineer, and such courses should of course be under the direction of the college of engineering. But an applied physics course of study should be designed, in my opinion, for the training of a particular kind of physicist, whose requirements are far different from those of an engineer.

The applied physicist must keep his main contact with the sources of new information, of new techniques, and of new theories. He must be thoroughly trained in fundamentals rather than in methods, though his training in methods may well be greater than that of the general physicist. But the chief difference in training should in my opinion be a difference in the fostering of enthusiasms, for enthusiasm is coming to be recognized as the most important element in any educational program. The physicist has had his enthusiasm aroused over the ferreting out of new secrets from nature—he learns to handle a pick well in digging for diamonds. The applied physicist needs to acquire similar dexterity in, and enthusiasm for, handling a shovel.

VII

The physicist who is to go into fundamental research proceeds from the particular to the general—here is some apparatus, let us see what we can find out with it. The applied physicist aims at the particular and utilizes the whole field of knowledge to attain his end—here is something that I want to accomplish, let us see how to do it. Most of the difference between the two is in the state of mind, and actually of course, the best physicists will always partake greatly of both characteristics. There have always been applied physicists of many sorts; the present flutter is only an attempt to learn to produce more of them as the demand has increased.

Most of the development of applied physicists thus far has been in the industrial research laboratories, in this country particularly in the

Bell Telephone Laboratories and in the research laboratory of the General Electric Company. It is not by accident that these two companies have the largest physics research laboratories in industry in this country, and have made the greatest contributions to industry through the application of fundamental physics. These companies have found that their ends were served most efficiently—and we must bear in mind that these were practical ends—by emphasizing the research aspect rather than the technical aspect, and letting the former nourish the latter rather than *vice versa*. This experience illustrates the desirability of letting the training of the applied physicist be handled by the school of science rather than the school of engineering. While new techniques occasionally produce new scientific discoveries, far more often are these techniques the result of scientific discoveries. It is easier for a physicist to become practical than it is for an engineer to keep abreast of progress in science.

It seems probable that before long we shall see this category which we are now calling applied physics again divided, with a special sort of research engineer bringing liaison between the applied physicist and the engineer. It is becoming increasingly common to plant two or three applied physicists in the midst of each engineering faculty. Civil engineers studying earthquakes need to know not only how to build a bridge that won't fall down, but how to apply vacuum tube amplifiers, servo-mechanisms and stroboscopes to the study of earthquake phenomena.

Towing tanks, wind tunnels, and railroad electrification systems all find themselves in need of the new pieces of apparatus which the applied physicists have been fashioning in the last few years as a result of the measurements, such as those on ionization potentials, made by researchers in fundamental physics only a few years ago.

VIII

The chief change in curriculum which appears necessary in attempting to handle the problem of the training of applied physicists, beyond this change in enthusiasms which has been mentioned, is to emphasize chemistry somewhat more and mathematics somewhat less, though with considerable flexibility still preserved. We recognize, of course, that there is such a thing as a theoretical or mathematical applied physicist, and the training of such a man might differ from that of an orthodox theoretical physicist only in having less emphasis on quantum mechanics and more on classical mechanics. The all-important difference is that one man is ultimately to focus his attention on macroscopic things, and the other probably on atoms and their parts. The problem reduces to convincing a certain fraction of the physics students that the problem of finding how to store sound waves and reproduce them without distortion, for example, is just as interesting and important in its way as is the dissection of an atom. The difference between being an ordinary physicist and being an applied physicist is largely a state of mind.

Excerpt from "Must We Have Another Boom?"

This brings us to technological progress as a protection against depression. Improvements in present products and methods, and the development of new products and methods, create new opportunities for investment. If the engineers, physicists, chemists, and others engaged in industrial research only make enough discoveries during the next five years, they will be able to create sufficient new opportunities for investment to offset the eventual drop in deferred demand.

As a simple illustration, consider the matter of housing. There are about 25,000,000 houses in the United States. The replacement demand for housing is small because the average life of a house is above fifty years. Improvements in design and materials, and reductions in cost sufficient to reduce the average life of a house to thirty or thirty-five years, would create an enormous replacement demand for housing. Suppose that by a series of improvements the cost of a house which is now $4000 was reduced to

$2500, and suppose that the $2500 house was substantially superior in design and materials. Such a reduction in cost is not unthinkable. It is far less than the reduction made during the last thirty years in the cost of automobiles. I do not venture to predict precisely how much the replacement demand for housing would be increased by a 37½ percent cut in the cost of construction, accompanied by improvements in design and materials. The increase would unquestionably be large. Indeed, it does not seem extravagant to predict that the replacement demand might be stepped up to 500,000 or 600,000 houses a year. Granted substantial technological progress, the building industry might be kept busy for twenty or thirty years replacing most of the present houses in America with better-planned, better-constructed, more convenient dwellings. It all depends upon how rapidly the engineers and others improve the product and reduce its cost.

Similar possibilities of creating investment demand exist in the field of railroad equipment, agricultural implements, public utility equipment, and industrial equipment in general. It is essentially a matter of technological progress. Consequently, it is beyond the control of the government, of economists, of money experts, and indeed of everyone except the engineers, physicists, chemists, and other industrial researchers and the business concerns for whom they work. From this statement a conclusion of first importance follows: The responsibility of avoiding a severe recession in business four or five years hence, after deferred demand begins to drop, rests above everything else upon the initiative and enterprise of thousands of business men scattered from one end of the country to the other and upon their willingness to spend money on industrial research. Business, in other words, is being presented with a test of its foresight and its resourcefulness. It must not rely upon government direction and planning to produce stability. The government, to be sure, has a highly important rôle to play. It must help by pursuing a wise budget policy, by controlling speculation and installment buying, by encouraging the reform of accounting practices, by building up unemployment reserves which will aid in preventing any recession in business from becoming cumulative, and by helping to discover incipient bottlenecks. None of these policies, however, will develop new sources of demand to offset the eventual drop in deferred demand which has accumulated during the last five or six years. This is the greatest problem of all, and it is one which only business men and their technical staffs can handle. Whether or not stability is achieved during the next decade will depend more than anything else upon how successfully the business men and their technicians create new opportunities for investment by improving equipment and products and by developing new products.

SUMNER H. SLICHTER
Atlantic Monthly, May, 1937.

Directional Ferromagnetic Properties of Metals*

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Introduction

DURING the last few years we have heard a great deal about the structure-sensitive properties of materials. More recently discussions of "order and disorder" in metallic alloys and even in inorganic mixed crystals, have become popular. Ferromagnetic properties are to be considered in both these categories. Among the structure-sensitive properties some of the magnetic properties show extreme variations, for example, the coercive force of what is commonly called pure iron may have any value from 0.01 to 20, while the maximum permeability may vary from 1000 to over 1,000,000, depending on the direction in the crystal parallel to which the property is measured, perhaps depending on the crystal size, but most of all depending on the state of purity and of strain in the material.

Ferromagnetic phenomena are also considerably affected by the amount of "order" in alloys, as shown particularly in the case of the Heusler alloys.[1] Ferromagnetism itself may be considered as an example of "order" in respect to orientation of atomic magnets, and the Curie point as the temperature of transition for order to disorder.

In this paper will be discussed the way in which various magnetic properties vary with direction in single crystals, chiefly in cubic crystals such as iron, nickel, and some of their alloys. Although the anisotropy constants of these materials are rather structure-*insensitive*, nevertheless they vary with composition in a way that lets us understand why, for example, the nickel-iron alloys containing from 50 to 80 percent nickel are particularly *sensitive* to strain and to several kinds of heat treatment, and why they exhibit other peculiarities which will be mentioned later.

General Background[2]

The simplest facts about magnetic anisotropy are illustrated in Fig. 1. This shows the structure of a single crystal of iron, which may be represented by a cube with an atom at each corner and one in the center, the whole crystal made up of such cubes packed together face to face. It is found experimentally that in the direction of an edge of this cube (a [100] direction) the magnetization curve labeled 100 is obtained. In the two other principal directions, the direction of a face diagonal and that of a cube diagonal, the other magnetization curves are obtained, as

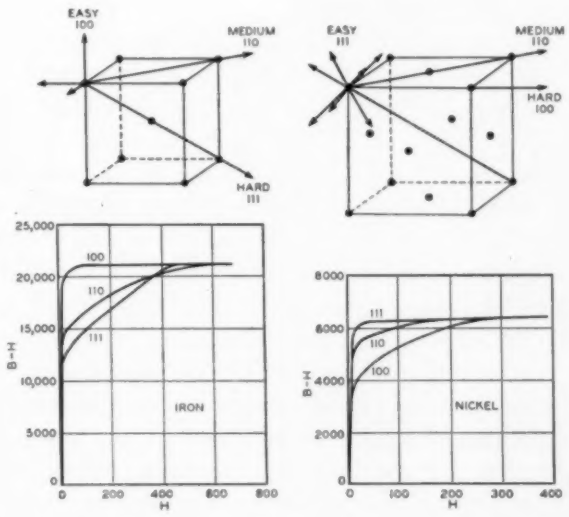

FIG. 1. Crystal structures of iron and nickel, and magnetization curves in principal crystallographic directions.

* Presented at the Symposium on the Structure of Metallic Phases held by the physics department of Cornell University, July 1–3, 1937.

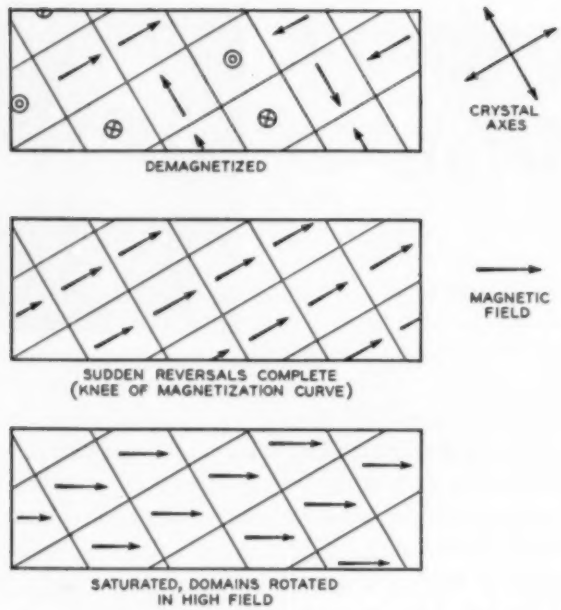

FIG. 2. Orientations of domains for various stages of magnetization.

shown. The structure of nickel may be represented also by an assemblage of cubes, with the atoms arranged in a different manner. The magnetization curves for nickel corresponding to the same three principal directions are shown also in the figure, and it may be seen that the curves are reversed in order from those of iron. In iron the [100] direction is said to be the direction of easiest magnetization and the [111] the direction of most difficult magnetization, whereas the reverse is true in nickel.

Before discussing anisotropy further, something more should be said about the structure of ferromagnetic materials and the mechanism of magnetization. We start with the idea due to Weiss, that the material is made up of domains of small size (approximately 10^{-8} cm^3), each domain magnetized to saturation in one of the directions of easy magnetization in the crystal in which it lies. These are shown schematically in Fig. 2 for a material in which, as in iron, the directions of easy magnetization are parallel to the crystal axes. In the unmagnetized condition the directions of magnetization in the various domains are distributed at random among the six equivalent directions so that the net magnetization is zero. When a moderate field is applied, most of the change in magnetization of the specimen as a whole consists in sudden changes in the direction, but not the magnitude, of the magnetization in the domains from one direction of easy magnetization to another. This is the "discontinuous" process of change in magnetization. A higher field causes the magnetization of each domain to change smoothly into parallelism with the field, and this final process is called the "rotational" change of magnetization.

Data for Iron-Silicon Crystals

The first important data on the anisotropy of iron containing 1.6 percent silicon were published in 1918 by K. Beck,[3] and are reproduced in Fig. 3 largely for historical reasons. They show a difference in permeability in different crystallographic directions, when the magnetization, I, is more than about half of the saturation magnetization, I_0. Compared with more recent results there is a large demagnetizing factor indicated by the departure of the dotted line

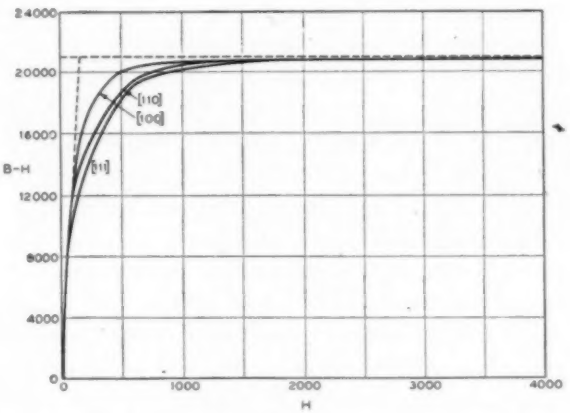

FIG. 3. Beck's magnetization curves for single crystal of iron-silicon.

from the vertical axis, and a relatively large area between this line, the curve for the [100] direction, and the horizontal line $I=I_0$ representing saturation magnetization. This area, $K_0=\int_0^{I_0} HdI$, is a measure of the energy necessary to magnetize to saturation in the direction of easy magnetization, and is about 70,000 ergs/cm^3 as derived from Beck's data.

Some data on crystals of iron containing 3.9 percent silicon have recently been reported by

H. J. Williams.[4] To avoid the errors of previous measurements he cuts his crystal specimens so that the magnetic circuit is closed and therefore the demagnetizing factor negligible. Fig. 4 (a) shows the manner of cutting the three specimens so that their sides make the desired directions with respect to the crystal axes, the sides of any one specimen being parallel to equivalent crystallographic directions. For measuring the magnetization curve for the [100] direction, one cuts out a hollow rectangle with its edges parallel to the crystal axes. The condition at the corners is uncertain, but the effect here can be made negligible by making the sides sufficiently long in comparison with the cross-sectional area. Similarly a [110] direction can be investigated by cutting the appropriate rectangle. In general a direction $[hkl]$ in a cubic crystal can be investigated by cutting a parallelogram whose sides have, in order, the directions $[hkl]$, $[kl\bar{h}]$, $[\bar{h}\bar{k}l]$, $[\bar{k}lh]$. The [111] specimen used has edges lying in the $(1\bar{1}0)$ plane. After cutting and etching the specimens were annealed for one hour in pure hydrogen at 1300°C. A photograph of them is shown in Fig. 4 (b).

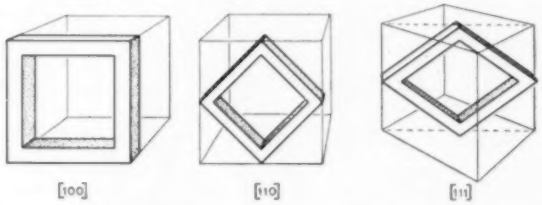

FIG. 4 (a). Method of cutting magnetic specimens for determining magnetization curves in [100], [110] and [111] directions.

The results of these recent measurements are shown in Figs. 5 (a) and (b), plotted on two scales in H. Several new things are apparent here. The anisotropy is found to extend to low fields, much below $I=I_0/2$, and has not been detected previously because of the large error in determining a small value of H in specimens with relatively large demagnetizing factors. This anisotropy for all values of I is brought out by the permeability (μ) *vs.* induction (actually μ *vs.* B–H) curves of Fig. 6. This figure shows also the unusually high values of μ_m attained, and the high ratio of 30 for the values of μ_m in the [100] and [111] directions. The value of K_0, equal to $\int_0^{I_s} H dI$ for the [100] curve of Fig. 5, is about 1000 ergs/cm³ or about one percent of that obtained by Beck, and indicates that the residual strains have been reduced greatly by the annealing which was in pure hydrogen at 1300°C.

After further heat treatment, in a magnetic field, the value of μ_m for the [100] specimen was raised to 1,380,000.

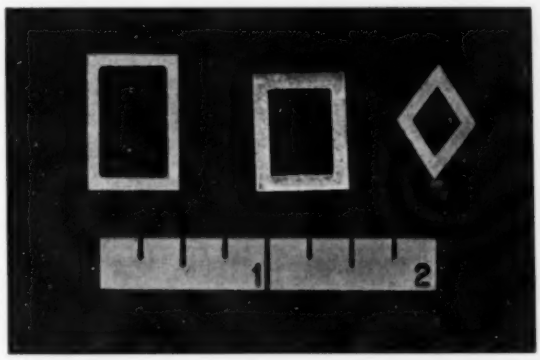

FIG. 4 (b). Photograph of specimens of iron-silicon used.

Theory of Anisotropy in High Fields[5]

As now developed, the theory assumes that the state represented by the middle portion of Fig. 2 is attained by the application of a very weak field. The theory accounts only for the final magnetization process, the gradual rotation of the magnetization vector out of a direction of easy magnetization toward the direction of the field. Thus there is associated with the magnetization, I_0, of a domain, a magnetic potential energy density which depends on the direction of the magnetization as defined by the direction cosines, S_1, S_2, S_3, referred to the cubic axes of the crystal. Expanding the energy in a power series of direction cosines, we have

$$E=K_0+K_1(S_1^2S_2^2+S_2^2S_3^2+S_3^2S_1^2)+K_2(S_1^2S_2^2S_3^2)+\cdots, \quad (1)$$

all lower power terms disappearing because of the symmetry of the cubic crystal. When a field is applied in a given crystallographic direction as indicated in Fig. 7, there will be additional energy stored,

$$-HI_0\cos\theta$$

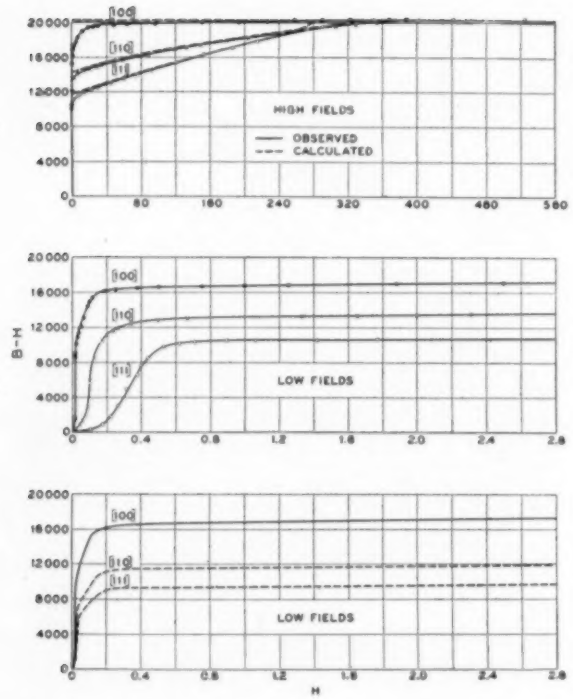

FIG. 5. Experimental and theoretical magnetization curves for iron-silicon single crystals, in high and low fields.

and the magnetization will find its position of minimum energy. In any plane of the crystal which contains a direction of easy magnetization, e.g., [100] in iron, this position is given by

$$(d/d\alpha)(E-HI_0\cos\theta)=0. \tag{2}$$

Thus

$$H=\frac{dE/d\alpha}{I_0\sin(\alpha_0-\alpha)},$$

I is given by

$$I=I_0\cos(\alpha_0-\alpha)$$

and the magnetization curve can be constructed provided the anisotropy constant (or constants) are known.

Our problem is then to find values of K_1 (and K_2) which will agree with the experimental curves. In Fig. 5 (b) are shown the theoretical curves (dashed lines) which can be compared with the data. Here $K_1=320{,}000$ and K_2 is relatively unimportant but has the approximate value of 100,000. The theoretical curves agree well with the data when $H>30$ but fail at lower fields as might be expected from the assumptions made in the theory.

Calculation of the I, H curve for the [110] direction is carried out as follows: In the (001) plane, use the [100] direction as reference direction ($\alpha=0$). Then for [110], $\alpha_0=45°$, $S_1=\cos\alpha$, $S_2=\sin\alpha$, $S_3=0$, $E=K_0+K_1(1-\cos 4\alpha)/8$, $dE/d\alpha=K_1(\sin 4\alpha)/2$, and

$$H=\frac{K_1\sin 4\alpha}{2I_0\sin(45°-\alpha)},$$

$$I=I_0\cos(45°-\alpha).$$

For this direction H and I are independent of K_2.

The potential energies E, calculated from Eq. (1) for the principal directions, are

$$\left.\begin{aligned}E_{100}&=K_0\\E_{110}&=K_0+K_1/4\\E_{111}&=K_0+K_1/3+K_2/27\end{aligned}\right\}. \tag{3}$$

But these energies are equal to the values of $\int_0^{I_s}HdI$, where H and I are measured in these directions. Or in general

$$E_{hkl}=\int_0^{I_s}H_{hkl}dI_{hkl},$$

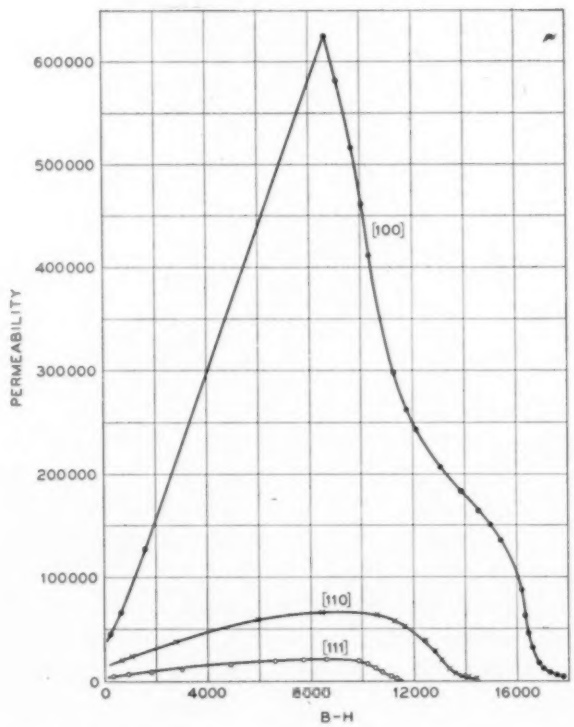

FIG. 6. μ *vs.* B-H curves corresponding to experimental curves of Fig. 5.

where the subscript *hkl* defines the crystallographic direction along which components of H and I are measured. Thus to determine the values of K_0, K_1 and K_2, the simplest procedure is to plot the magnetization curves to $I=I_0$ for the principal directions, measure the areas to the left of each curve, and use Eqs. (3) put into the form:

$$K_0=E_{100},$$
$$K_1=4(E_{110}-E_{100}),$$
$$K_2=27(E_{111}-E_{100})-36(E_{110}-E_{100}).$$

Values for the K's for various materials at various temperatures are given in a later section.

Anisotropy in Low Fields

The data of Figs. 5 (a) and 6 show that there is considerable anisotropy when the intensity of magnetization is less than half of the saturation value. As mentioned above this is a new observation and there has been no theory to account

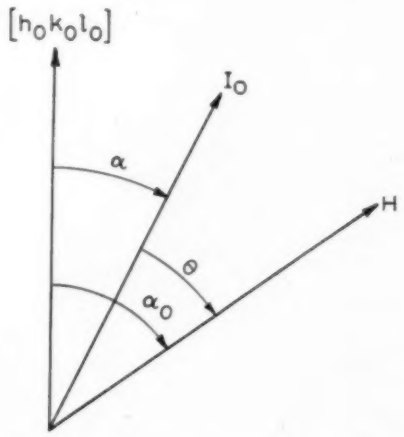

FIG. 7. Relation between vectors in an [*hkl*] plane.

for it, in fact it is contrary to the usual statements regarding the data and to the assumptions underlying the theory. However, a simple analysis based on our present conceptions of magnetic domains shows that such anisotropy should be expected.

It is understood that according to theory, in fields of the order of one oersted the local magnetization in iron will always be parallel to a cubic axis within a small fraction of a degree. Then if a single crystal is magnetized in the [110] direction by a small field H, as shown in Fig. 8, this field will be effective only because it has a component $H/\sqrt{2}$ in a [100] direction. This field will produce a magnetization, I_{100}, in the [100] direction according to the I, H curve as determined for this direction. Then this magnetization

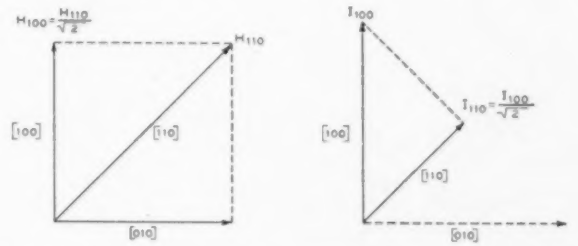

FIG. 8. Relations between H and I vectors in low fields when [100] is direction of easy magnetization.

will be effective in the [110] direction, the direction of the applied field, only to the extent that it will have a component $I_{100}/\sqrt{2}$ acting in this direction. Thus starting from a point on the [100] curve, one reduces the ordinate by a factor of $\sqrt{2}$ and increases the abscissa in the same ratio, to obtain a point on the [110] curve. A magnetization curve for the [111] direction can be constructed similarly by using the factor $\sqrt{3}$ instead of $\sqrt{2}$.

According to this simple theory the initial permeabilities in the [100], [110] and [111] directions should be in the ratio $1 : 1/2 : 1/3$.

Theoretical [110] and [111] curves have been constructed from Williams' experimental [100] curve, and are shown in Fig. 5 (c).

The calculated curves resemble the observed ones in many respects, so that the simple theory may be regarded as representing the first approximation. But comparison of Figs. 5 (b) and 5 (c) indicates that there is still a large discrepancy and that a more complete theory is to be desired.

Torque Measurements

The anisotropy constants can be determined not only by the method described, but also by measuring the torque[6] on a disk or oblate spheroid in a high magnetic field. The torque per unit volume is

$$L=-dE/d\alpha,$$

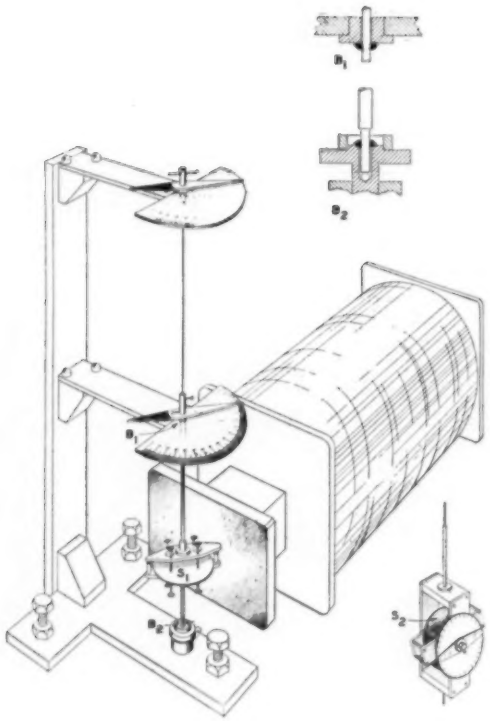

FIG. 9. Torque magnetometer of H. J. Williams, with half of electromagnet removed.

where α is the azimuthal angle about a selected torque axis. In a (100) plane of a single crystal the torque about [001] is

$$L_{001} = -(K_1/2) \sin 4\alpha$$

and in a (110) plane

$$L_{110} = -(K_1/8)(2 \sin 2\alpha + 3 \sin 4\alpha) - (K_2/64)(\sin 2\alpha + 4 \sin 4\alpha - 3 \sin 6\alpha). \quad (4)$$

The torque magnetometer used by Williams to determine L, α curves, is shown in Fig. 9. The sample is shown at S_1, clamped on a shaft mounted in jeweled bearings. The lower scale indicates the orientation of the disk, the difference in readings between the two scales is a measure of the torque which is produced by the action of the magnetic field and compensated by twisting the phosphor-bronze wire connecting the two pointers.

Data[4] for a disk of silicon-iron, cut to a (110) plane, are shown in Fig. 10. The solid line is the theoretical curve for $K_1 = 287{,}000$, $K_2 = 100{,}000$.

The torque magnetometer is a useful instrument in a variety of ways. In almost all fabricated materials there are preferential arrangements of the component crystals. By way of example, torque curves for hard-rolled and for annealed nickel are shown in Fig. 11. The form of the curve of Fig. 11 (a), indicates, in agreement with x-ray data, that during the rolling operation the crystals tend to arrange themselves with their (110) planes in the plane of the sheet and their [$\bar{1}11$] directions parallel to the direction of rolling. In the same sheet after annealing for one hour at 1000°C, the torque curve in Fig. 11 (b) indicates a cubic texture, a (100) plane in the rolling plane and [001]

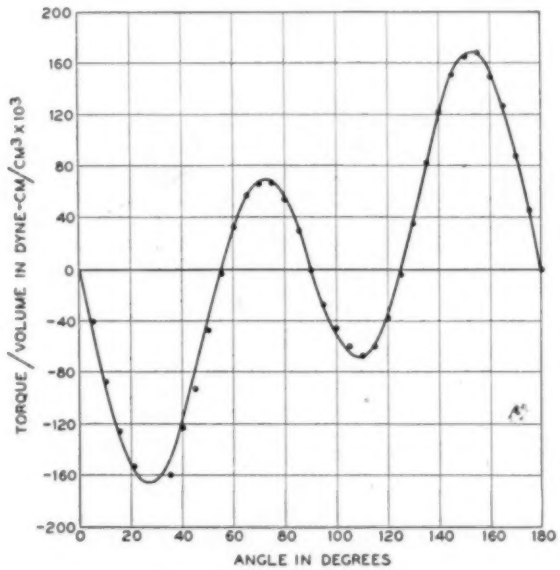

FIG. 10. Torque curve of single crystal disk of iron-silicon, in (110) plane. The line is drawn according to Eq. (4) with $K_1 = 287{,}000$, $K_2 = 100{,}000$.

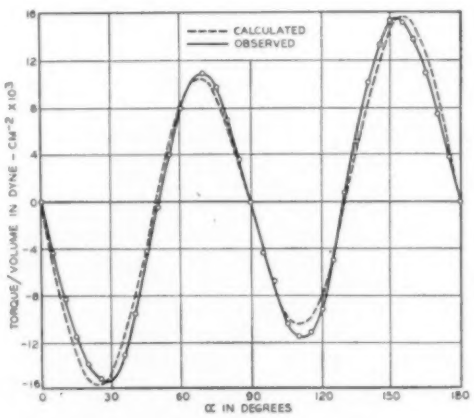

FIG. 11 (a). Torque curve for unannealed disk of rolled sheet nickel. The direction of rolling is $\alpha = 0$.

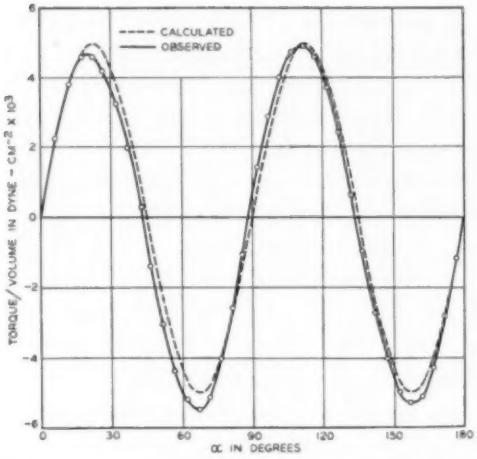

FIG. 11 (b). Same after disk was annealed at 1100°C for 14 hours.

directions parallel to and at right angles to the direction of rolling. The maximum torque in each specimen may be compared with the value calculated for a single crystal having the orientation preferred by the crystals of the sheet, and is a measure of the perfection of the alignment obtained. For nickel the maximum torques per unit volume for the single crystals are 12×10^3 and 17×10^3 dyne cm^{-2} for (a) and (b), respectively, using the value of K_1 given in Table II. The fact that the torque for the hard-rolled specimen is observed to be higher than that calculated for the single crystal indicates that the assumed value of K_1 for nickel may be too high. The value $K_1=-51\times10^3$, given by Gans,[17] leads to a predicted maximum of 18×10^3, somewhat higher than that observed, as should be expected. Even using this higher value of K_1 the torque curve indicates a high perfection of alignment of the crystals in the hard-rolled material.

The method of torque measurements can be used for determining preferred orientations in crystals when the preference is so slight that it is difficult or impossible to detect it by means of x-rays. If the effect of K_2 does not overshadow that of K_1, simple types of preferred orientations can be determined[7] by the magnetic method except for rare ambiguities.

A simple determination of the direction of easy magnetization in fabricated material is often of interest in the manufacture of magnetic material and the stamping of parts of magnetic apparatus from rolled sheet. In Table I[8] are given the directions of easy magnetization in a number of materials rolled into sheets, in the unannealed and annealed conditions. The angles in columns 2 and 3 are those between a direction of easy magnetization and the direction in which the material was rolled.

TABLE I. *Directions of easy magnetization in rolled sheets.*

Material	Angle with Rolling Direction	
	Hard Rolled (Degrees)	Annealed (Degrees)
Nickel	0, 90	45 (a)
Iron	45	0, 90 (b)
Fe+3.5% Si Hot Rolled	—	0 (c) (d)
Fe+3.5% Si Cold Rolled	—	0, 90
Fe+4.5% Mo	45	0 (a)
78 Permalloy	0	0 (a)
78 Permalloy	0	90 (c)
45 Permalloy	0	90 (a)
3.8–78 Cr-Permalloy	0	0 (a)
3.8–78 Mo-Permalloy	0	90 (a)
49% Fe, 49% Co, 2% V	90	0 (a) (e)

(a) Annealed for 1 hr. at 1000°C. (c) Annealed for 1 hr. at 1200°C.
(b) Annealed for 2 hrs. at 880°C. (d) In low fields, 0° and 90°.
(e) In low fields, 45°.

Effect of Composition

The anisotropy of one alloy of iron and silicon has been discussed in some detail. The question now is, how do the anisotropy constants depend on chemical composition and crystal structure, and how do they vary with temperature? In an attempt to answer this question, McKeehan[9] and his students have made a survey of the iron-cobalt-nickel alloys, and some of the results are shown in Fig. 12. Lines pointing upwards represent a positive K_1, those pointing downwards a negative value.

There are several interesting points on this diagram, one is that there is no apparent sudden change in K_1 when the crystal structure changes from face-centered cubic to body-centered cubic. Combining this observation with another, namely, that the anisotropy constant is the same or nearly the same when the material is hard worked as it is when annealed,[10] it can be said that K_1 is not very structure-sensitive.

TABLE II. *Values of K_1 and K_2 for various Fe-Co, Fe-Ni, Co-Ni and Fe-Co-Ni alloys.*

Composition Fe	Co	Ni	Temp. °C	$K_1 \times 10^3$ erg/cm³	$K_2 \times 10^3$ erg/cm³
100			20	421	150
			200	300	220
70	30		20	102	160
60	40		20	45	−110
50	50		20	−68	−390
30	70		20	−433	50
50		50	20	33	−180
			200	25	−80
35		65	20	15	−70
			200	12	−40
30		70	20	6.8	−17
			200	1.5	−4
10		90	20	−7.0	−23
			200	−2.0	−10
	65	35	20	−258	150
	50	50	20	−108	−40
	40	60	20	−74	40
	20	80	20	−3.5	8
	10	90	20	15.7	−40
	03	97	20	−10	9
		100	20	−34	50
			200	5.0	20
50	10	40	22	61	−160
			200	19	4
			398	7.4	−60
25	25	50	22	3.5	16
			205	3.8	2
			398	−2.5	22
20	15	65	22	9.1	−110
			201	−0.8	−18
			398	−3.2	2
15	25	60	22	−26	34
			201	−10.3	−45
			398	−3.3	−15
10	40	50	22	−72	−4
			205	−54	41
			398	−8.7	−100
10	30	60	22	−38	−80
			203	−17	−50
			397	−12	−37
10	20	70	22	−29	17
			200	−25	70
			398	−13.8	29
			598	0.0	−6
10	10	80	22	−2.0	−39
			200	−2.0	−20
			400	−1.6	6
			516	−3.2	21

Values of K_1 and K_2 for Fe-Co-Ni alloys for which data have been published are given again in Table II, taken from the paper by McKeehan.[9]

The relation of anisotropy to atomic structure has been discussed recently by Bozorth and McKeehan,[10] and an extended analysis given by McKeehan.[11]

Alloys Having Weak Anisotropy

The most interesting alloys are those for which K_1 is small, alloys having compositions near 75 percent Ni and 25 percent Fe and near 40 percent Co and 60 percent Fe, as well as many ternary alloys. Values for the iron-nickel binary series are shown graphically in Fig. 13 because of their special interest. More data are desirable, but the indication is that K_1 passes through zero between 75 and 80 percent nickel, and that K_2 is also very small in this region.

One of the peculiarities of the iron-nickel alloys is that the order of increasing ease of magnetization, [111], [110], [100] as for iron, or the reverse order as for nickel, is not always followed. In the 50 percent nickel alloy [100] is the direction of easiest magnetization, [110] is the hardest and [111] is intermediate, as observed by Kleis.[9] This observation is incompatible with the theory if the expression for E, Eq. (1), contains only the terms involving K_0 and K_1; for if K_1 is positive we have the order as for iron and if negative that as for nickel. But a complete explanation[12] can be given by including the K_2 terms. If K_1 and K_2 are opposite in sign and the absolute value of the ratio K_2/K_1 is greater than 9/4, the energies required for magnetization to saturation in the [100], [110] and [111] directions can be abnormal. Thus each of the six possible orders of ease of magnetization

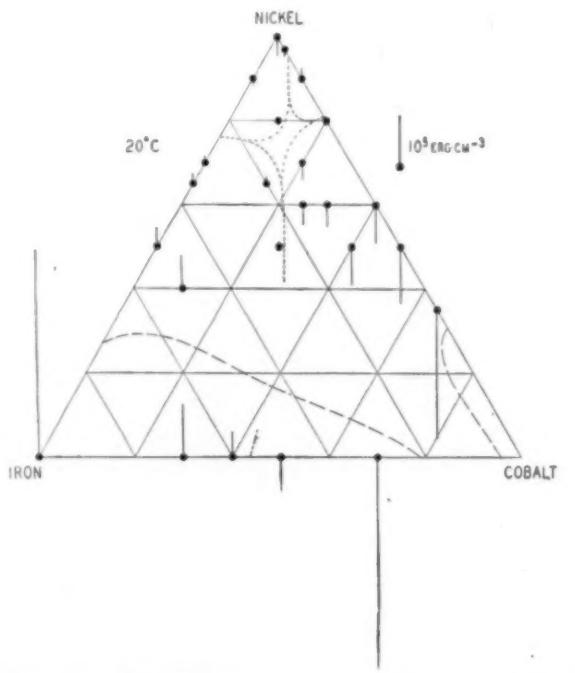

FIG. 12. Anisotropy constants, K_1, for Fe-Co-Ni alloys.

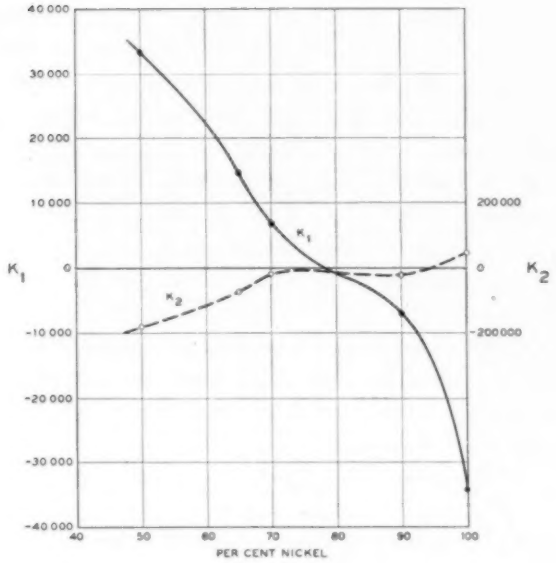

FIG. 13. Anisotropy constants for γ Fe-Ni alloys at room temperature. The scales of K_1 and K_2 are adjusted so that equal vertical distances correspond approximately to equal energies when averaged for all possible crystallographic directions.

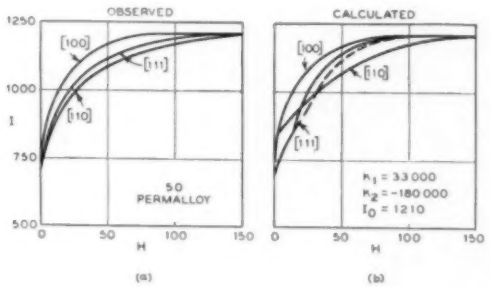

FIG. 14. Experimental and theoretical magnetization curves for 50 permalloy single crystals, having the unusual order of ease of magnetization: [100], [111], [110].

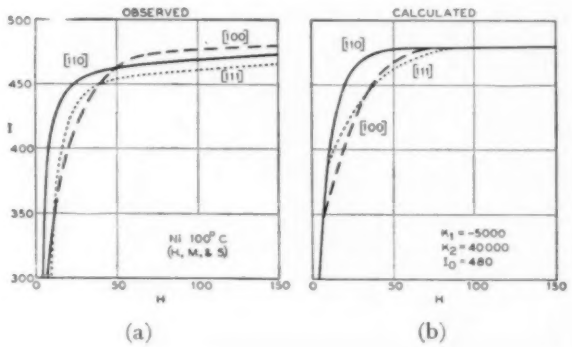

FIG. 15. Experimental and theoretical magnetization curves for nickel at 100°C, showing the order of ease of magnetization: [110], [100], [111].

corresponds to real values of K_1 and K_2. In Fig. 14 are shown the calculated[12] and observed[9] curves for 50 permalloy. Here the order of increasing E, as determined by $\int_0^{I_0} H dI$, is [100], [111], [110].

There is some evidence that in nickel at 100°C the order is [110], [111], [100], for which according to theory $K_1 < 0$, $|9K_1/4| < K_2 < |9K_1|$. The theoretical curves drawn with constants satisfying these conditions are given in Fig. 15 (b), to be compared with the data[14] of Fig. 15 (a).

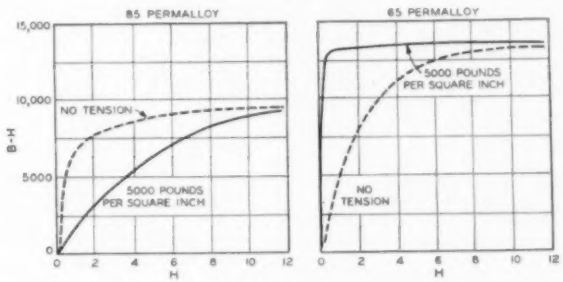

FIG. 16. Effect of tension on the magnetization of 85 and 65 permalloys. (5000 lbs/in^2 = 3.5×10^8 dynes cm^2).

Effects of Stress

But the most interesting of the consequences of a small value of K_1 is the relatively high strain-sensitivity of the magnetic properties. Fig. 16 shows how much a moderate tension affects the B, H curves[14] for alloys in this general region of composition near 70 percent nickel, 30 percent iron. (The opposite directions of the effects are of course connected with the opposite signs of the Joule magnetostriction constant for these alloys, and when this constant is small the strain-sensitivity is also small even though the anisotropy is weak.) In this range of compositions are found also especially large effects of heat treatment,[15] as shown in Fig. 17. Alloys containing between 50 and 90 percent nickel respond to a change in cooling rate after annealing or to heat treatment in a magnetic field. This is due partly to the fact that in this range the Curie points are high enough so that the material can be magnetic at the same time that it is being annealed—that is, the Curie point is above the lowest temperature at which the material softens rapidly after hardening by cold work. It is due

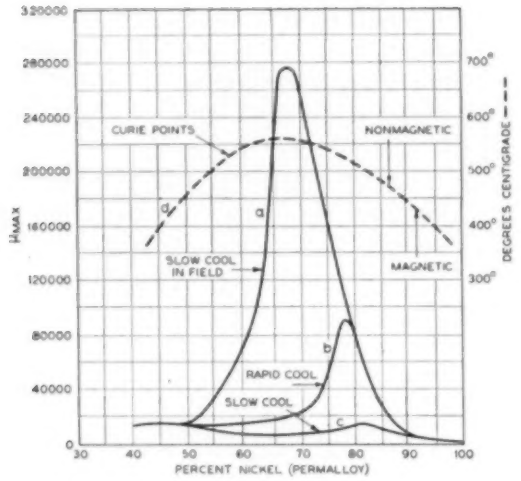

FIG. 17. Effect of heat treatment on the permalloys showing the sensitive region from 50 to 85 percent nickel.

partly, also, to the fact that the anisotropy energy E is not too large compared with the magnetic energy of magnetostriction. For an example of the other extreme case, in iron the effect of heat treatment in a field is small in spite of the high Curie point, because the energy of anisotropy is large compared with the magnetic energy of magnetostriction.

As calculated by Becker and Kersten[16] the magnetic energy per unit volume due to a stress σ is

$$F=-\tfrac{3}{2}\lambda_s\sigma(\cos^2\theta-\tfrac{1}{3})$$

where λ_s is the magnetostriction at saturation (assumed isotropic) and θ is the angle between the stress (tension) and the magnetization. This term must be added to the other two already discussed, to determine the position of minimum energy for the magnetization of a domain. Thus the more complete expression corresponding to Eq. (2) is

$$(d/d\alpha)[E+F-HI_0\cos(\alpha_0-\alpha)]=0.$$

The quantities E and F are about equal in iron when the stress $\sigma=50\times10^8$ dynes/cm², in nickel when $\sigma=1.3\times10^8$. These stresses may be compared with those at the yield points, which for each metal are about 15×10^8 when annealed and 70×10^8 when severely cold worked. For the hard worked materials the stresses at the yield points are also those for rupture.

In unalloyed iron and nickel, F is comparable in magnitude to E only when the applied stresses are high. When there are no stresses applied externally there may still be internal stresses in well-annealed materials due to the magnetostriction of the domains, and it is interesting to consider under what conditions, in what materials, these are important. It is assumed that these stresses will lie in the direction of easiest magnetization and be equal in magnitude but opposite in sign to the saturation-magnetostriction in that direction (λ_s is now not necessarily isotropic). Under these conditions $F=-\lambda_s\sigma$ and $-\sigma=\lambda_s Y$, so that

$$F=\lambda_s^2 Y$$

where Y is Young's modulus. To take a typical case, for 70 permalloy $\lambda_s=18\times10^{-6}$ in the [100] direction, and $F=700$. This may be compared with the value of E averaged[17] over all crystal orientations,

$$K_1/5+K_2/105=1360-160=1200.$$

Thus $F=700$ is an important part of $E+F=1900$.

During heat treatment the magnetostriction strains are more or less relieved depending on the rate of cooling, the height of the Curie point in relation to the annealing temperature, and other factors. So it is not surprising that 70 permalloy is susceptible to heat treatment. At about 77 percent nickel K_1 passes through zero and K_2 is very small, consequently F is an even larger fraction of the whole potential energy.

It has been suggested by Bitter[18] that randomly directed internal strains may account for the energy of magnetization in the direction of easy magnetization. In a well-annealed single crystal having a positive K_1, the K_0 term is known to be of the same order of magnitude as $\lambda_s^2 Y$. Comparison of K_0 and $\lambda_s^2 Y$ for a single crystal of 66 permalloy is made in the last section. Comparison for the silicon-iron crystal examined by Williams is difficult because λ_s is not known for the [100] direction.

Anisotropy of Hexagonal Cobalt

Because cobalt crystals are hexagonal at room temperature the energy function[19] corresponding

to Eq. (1) for cubic crystals is

$$E=K_0+K_1S_1^2+\cdots,$$

where S_1 is the direction cosine of the magnetization with respect to the hexagonal axis, [00·1]. At the present time the higher power terms seem to be unnecessary to satisfy the data available. This means that within the limit of error, the ease of magnetization depends only on the angle

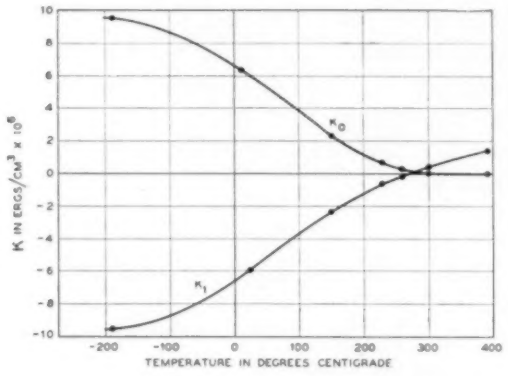

FIG. 18. Dependence on temperature of anisotropy constants of hexagonal cobalt.

between the magnetization and [00·1] and there is no anisotropy in the plane perpendicular to this axis. Since it is found by experiment that [00·1] is the direction of easy magnetization at room temperature, K_1 is then negative. As in the case of cubic crystals, the constants can be determined from the values of $E=\int_0^{I_0}HdI$ for various directions:

$$K_0=E_{10\cdot0},$$
$$K_1=E_{00\cdot1}-E_{10\cdot0}.$$

The values of the constants, as derived from the data of Honda and Masumoto,[20] are plotted against the temperature in Fig. 18. K_1 changes sign at about 270°C, above this temperature a crystal is magnetized most easily in a direction at right angles to the hexagonal axis. At 477°C cobalt becomes cubic and in this form no data concerning its anisotropy are available.

Effect of Temperature

Values of K_1 for iron have been determined[21] in the whole temperature range from −180°C to the Curie point, and are shown in Fig. 19 in which is plotted also the saturation magnetization for comparison. Below room temperature the curve seems to flatten and approach absolute zero with a horizontal tangent, in much the same way as the I_0 *vs.* T curve. Some rough data for K_2 also are plotted here.

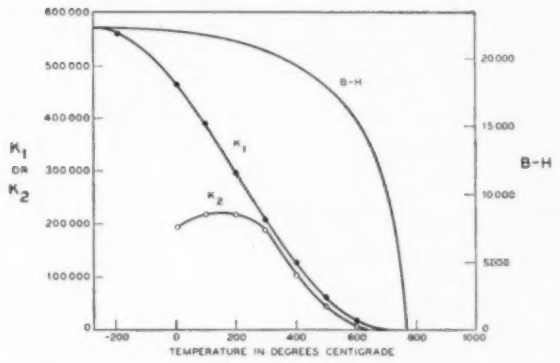

FIG. 19. Dependence on temperature of anisotropy constants of iron.

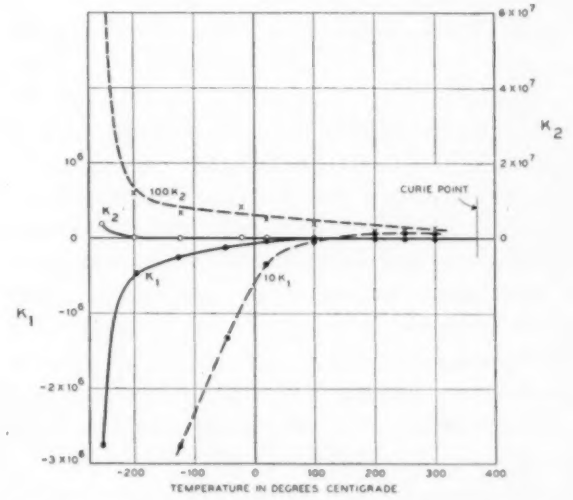

FIG. 20. Dependence on temperature of anisotropy constants of nickel.

The data for nickel[13] are quite incomplete but nevertheless show that for this metal K_1 varies with temperature in quite a different way. See Fig. 20. Measurements have been carried down to 25°K and here the extrapolated magnetization curves indicate that $K_1=-2.8\times10^6$, the absolute magnitude being over 5 times as great as the greatest observed for iron. Whereas the K_1 of iron increases only about 10 percent below room temperature, that for nickel increases by a factor of about 80. There is no theory to account for this change, the theory which has been pro-

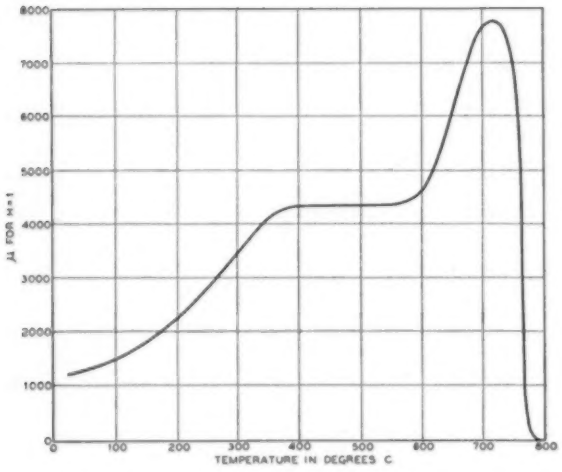

FIG. 21. Hopkinson effect in iron showing low anisotropy just below Curie point.

posed[22] for iron is incompatible with the data for nickel at these low temperatures.

At temperatures some two or three hundred degrees below the Curie point, the anisotropies of both iron and nickel are only small fractions of what they are at room temperature. This seems to be the explanation of the long-known Hopkinson effect,[23] according to which the permeability-temperature curve, for a constant moderate field, rises to a peak just below the Curie point. This effect is shown in Fig. 21.[24] At the maximum at about 700°C the material is nearly saturated in a field of one oersted, and this means that the anisotropy has practically vanished.

New Results on Single Crystals

In an attempt to learn more about the effects of anisotropy and strain in low fields, for which the magnetization is considerably less than that given by theory, Cioffi, Williams and Bozorth[25] have prepared and measured single crystals of two compositions. In preparing the first crystal it was attempted to make iron as pure as possible, and in doing this some improvements were made on the method used by Wells, Ackley and Mehl.[26] A piece of carbonyl iron, prepared in Germany and almost spectroscopically pure except for certain nonmetallic elements, was placed inside a cylinder made of the same material. Through this was passed hydrogen which had been purified by passing through a 1/4 mm wall of palladium at 700°C. The cylinder and specimen were then heated and maintained at 1500°C for 28 hours, to reduce the contents of carbon, oxygen and sulfur. The furnace was then cooled to 880°C, just below the $\alpha-\gamma$ point, and maintained there for another 24 hours to permit crystals to grow in the α phase. From the sheet was cut a hollow rectangle, 8 mm×9 mm outside dimensions, each side 1.5 mm square in cross section and parallel to a [100] direction.

Spectrochemical analyses, accurate to about one-fourth of the quantities reported, and chemical analyses for carbon and sulfur, are shown in Table III. The amount of oxygen was estimated by comparison with analyses of other samples of iron similarly treated.

TABLE III.

ANALYSIS OF HIGH PURITY IRON		AMOUNTS IN PERCENT	
Ni	0.008	Mn	<0.001
Co	<0.001	Cu	<0.005
Si	0.002	C	0.008
Cr	<0.001	O	<0.001
Mo	<0.001	S	0.001

After cutting, the magnetic specimen was annealed for 18 hours at 880°C and etched. It was found to be still a single crystal except for a few small inclusions in the surface estimated to occupy about 2 percent of the total volume. These had apparently been caused by recrystallization of material which had been strained during the cutting and filing operations and not removed by etching.

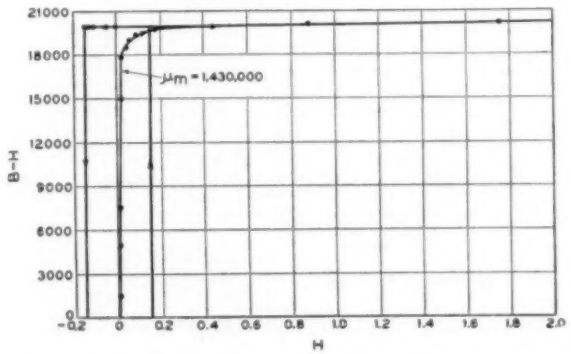

FIG. 22. Magnetization curve and hysteresis loop of pure crystal of iron in [100] direction, showing high permeability.

Some magnetic data are shown in Fig. 22. The magnetization curve was determined by repeated cycling of the field, starting with a high field and gradually reducing it. At the lowest induction attainable by the usual methods of demagnetization, $B=18{,}000$, the permeability was a maximum and equal to 700,000. Hysteresis loops were recorded photographically. Later, by careful manipulation the residual magnetization has been reduced and at $B=17{,}500$ a maximum permeability of 1,430,000 was attained.

One unexpected result of these measurements is the large coercive force, 0.15, of pure iron. Although smaller than for ordinary iron it is ten times as large as has been obtained for less pure polycrystalline iron, it is also considerably larger than for the single crystal of silicon iron after magnetization in a high field. Accordingly this is evidence against the opinion held by a number of physicists that a pure crystal has zero coercive force and hysteresis loss.

The second crystal had the composition 66 percent nickel and the rest iron, and was prepared by slow freezing of the melt in a carefully controlled atmosphere. About 500 grams solidified as a single crystal, and from this Williams cut a "picture frame" with sides parallel to [100] directions.

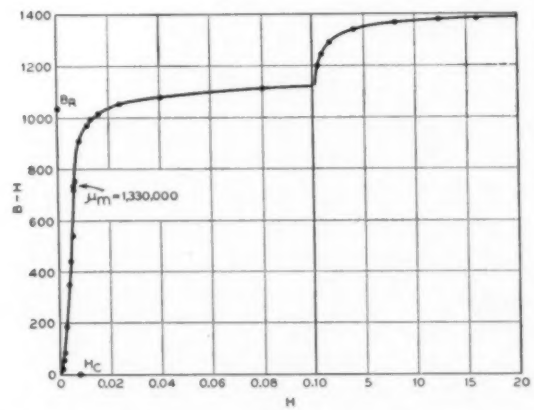

FIG. 23. Magnetization curve of single crystal of 66 permalloy in [100] direction.

This material is interesting because it has very weak anisotropy, a considerable magnetostriction, and a Curie point (*ca.* 600°C) high enough so that the material can be annealed while still magnetic. These are just the properties which a material must have to be affected by heat treatment in a magnetic field,[27] and this material was chosen partly for that reason. The rectangular specimen, after cutting and etching, was annealed for 18 hours in pure hydrogen at 1360°C, just below the melting point. It was then heat-treated at a lower temperature, once in the absence of a field and again in the presence of a field of 10 oersteds. With no field during heat treatment the maximum permeability was 18,000; with the field the permeability was as high as 1,330,000. Some of the data are shown in Fig. 23.

The maximum permeabilities of these two single crystals and of the single crystal of silicon iron described in the third section, are all above a million and are the highest that have been reported for any materials. The coercive force of the 66 permalloy crystal is 0.0064 and the K_0 value about 800 ergs/cm^3, both the smallest ever recorded. The latter may be compared with $\lambda_s^2 Y$ which is 650, a close agreement considering that a slight uncertainty in the saturation magnetization makes a relatively large error in K_0.

The high values of permeability at all values of magnetization, and the low hysteresis loss, have been attained as previously mentioned by combining several factors each one of which is known to increase the permeability. These will be recapitulated here and may serve as a kind of summary of the experimental results for the so-called soft magnetic materials: (1) Absence of strains associated with hard-working, dissolved interstitial impurities and grain boundaries: (2) choice of proper crystallographic direction for magnetization; choice of composition for which (3) the anisotropy is small and (4) the Curie point is well up in the annealing range of temperature; and (5) the presence of a magnetic field during heat treatment.

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Expenses of the Chrysler Corporation had to be cut during 1931, 1932 and 1933. We had to cut salaries, reduce operations, retrench in almost every way. There were bleak months when the plants, for lack of orders, were operating down to 40 per cent of capacity. But no matter how gloomy the outlook, I never cut one single penny from the budget of our research department. I think Carl Breer, who runs the research, will bear me out in this. I can't recall that he was asked to stint on anything. The reason for that is something that any modern industrialist knows and understands. The research of today is what will be keeping a soundly managed industry alive and healthy five and ten years in the future. As the depression became worse, as people became more gloomy, we grew bolder in our research. The things that were developed in the laboratories in those dark days are the improvements that created a strong demand for cars in 1936 and 1937. Research is the answer, if anyone should ask why today's cars are so much improved; it is why the automobiles of 1945 will be incomparably better than any we have seen.

From "Life of an American Workman" by Walter P. Chrysler in collaboration with Boyden Sparkes in August 14, 1937 issue of *The Saturday Evening Post.*

The Industry of Solid Carbon Dioxide

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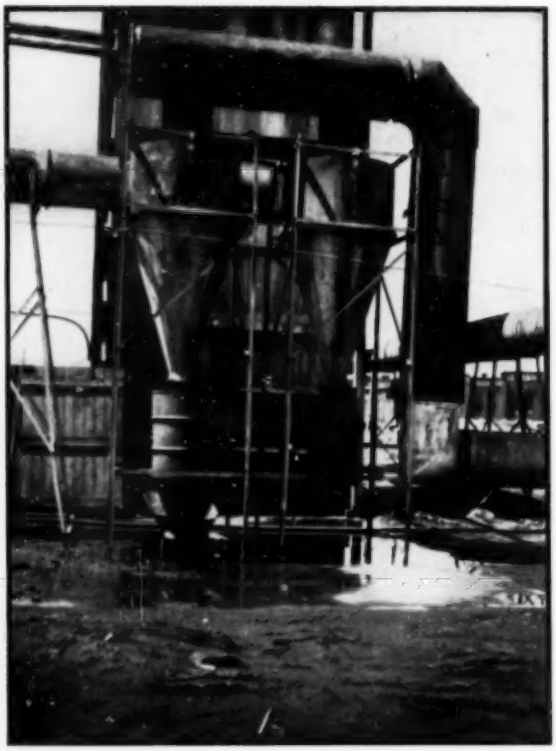
SOLID carbon dioxide has grown up during the past decade. In 1936, the estimated sales of this material in the United States reached 142,000 tons. Thus from a laboratory convenience first sold in this country in 1926, it has become in a bare ten years an important commodity made in 50 plants located in 29 states. Abroad its commercial importance is not so great, but nevertheless 60 plants are engaged in its manufacture in Canada, England, Germany, Australia, New Zealand, Japan, Africa and South America.

By its picturesque properties and its phenomenal growth, solid carbon dioxide has attracted numerous inventors and investigators who have sought to improve its manufacture and widen its usefulness. The number of patents granted in the United States relating to this art runs literally into the hundreds despite the fact that the material itself, first made by Thilorier in 1835,[1] is not subject to patent.

The properties of solid carbon dioxide are sufficiently unusual to suggest a host of applications. Most important of these are the fact that it sublimes directly from the solid to the gaseous state at pressures below 5.11 atmospheres. At one atmosphere, the temperature of sublimation is −78.5°C (−109.3°F), which is far below any required in industry except in the most unusual cases. Liquid air is, of course, much colder but also much more expensive.

The gas evolved during sublimation has many valuable properties since it is extremely pure, anhydrous carbon dioxide. Although it is commonly considered to be an inert gas, obviously it is only so with respect to oxidation and reduction at ordinary temperatures. At elevated temperatures it becomes an oxidizing agent. In the presence of moisture it produces a distinct acid reaction. Living things, both animal and vegetable, are profoundly affected by carbon dioxide. With respect to air and moisture, its higher molecular weight encourages the diffusion of these gases into itself in a way to produce actually measurable pressure. Rubber is highly permeable to carbon dioxide, so much so that a toy balloon partially inflated with air will actually blow itself up to the bursting point when immersed in an atmosphere of pure carbon dioxide. Another especially important characteristic of the gas is its relatively high insulating value against heat. For practical purposes a quiescent layer of dry carbon dioxide (confined to prevent convection) has about 50 percent more insulating value than a similar layer of dry air and part of this greater value is imparted to fibrous insulants in which carbon dioxide replaces air. These characteristics of the evolved gas are often overlooked but necessarily play vital roles in the utilization of solid carbon dioxide.

Thermal characteristics give solid carbon dioxide its primary usefulness. On the phase rule diagram, the two important points are the triple point, occurring at −56.6°C and 5.11 atmospheres pressure, and the critical point at 31.0°C and 75.79 atmospheres pressure. The liquid cannot exist at temperatures below that at the triple point nor at lower pressures than 5.11 atmospheres. Similarly the gas cannot be liquefied at temperatures above 31.0°C. Anomalous as it may seem, above the critical temperature and at sufficiently high pressures gas and solid are again in equilibrium. Indeed, this remarkable fact has been suggested as a method for the direct solidification of gas, albeit without



Dust collectors remove fly ash from flue gas from coke breeze fire. Plant of International Carbo-Ice, Ltd., Toronto.

commercial success to date on account of the tremendous pressures involved.

Because of the location of the triple point, solid carbon dioxide has no true melting point in the ordinary sense, except under substantial pressure, but sublimes directly to gas. This fact has been of the utmost significance in the commercial use of this material for refrigeration purposes. Its effect has been twofold: the latent heat of sublimation, equivalent to the sum of the latent heats of fusion and of vaporization, is relatively high thus permitting the storage of a large amount of negative heat in small weight and bulk; and since no liquid phase is involved in sublimation it has been practicable to build commercially useful refrigerated containers from light-weight materials impossible to use if liquids are involved.

A fact of high secondary importance in the application of solid carbon dioxide to refrigeration has been its high specific gravity, which coupled with its high latent heat, materially reduces the space required for storing a given amount of cooling effect. (Table I.)

Process of Manufacture

Manufacture of solid carbon dioxide as normally practiced consists of three essential steps:

1. Concentration and purification of the gas.
2. Liquefaction of the gas.
3. Solidification.

Necessarily the details of these steps are modified by circumstances, particularly the first which must be adapted to the handling of the raw material available. One may conveniently divide carbon dioxide sources into those yielding substantially pure gas (95 percent or more) containing no nitrogen, oxygen or other "permanent" gases and others in which impurities of this character predominate. Into the first category fall the gases produced in alcoholic fermentation and as by-products in several chemical operations, and that from certain natural wells. In the second group are gases from combustion, from lime and cement kilns and from other natural wells and springs of high "permanent" gas content.

Purification in the two groups is carried out with distinctly opposite effects. High concentration gas is treated to remove impurities from the carbon dioxide but in low concentrations the carbon dioxide is removed from the impurities.

Fermentation gas, for example, may be washed successively with water and with sulfuric acid and then passed under pressure over activated carbon or silica gel to remove residual odors. Other treatments with chemical reagents (oxidizing agents and adsorbents) have been suggested to remove odorous impurities. The de-

TABLE I. *Physical properties of solid carbon dioxide.*

Specific Gravity (commercial product)	1.5
Latent Heat of Sublimation (−78.5°C)	136.9 cal./g 246.4 b.t.u./lb.
Specific Heat of Gas (178.5°C to 0°C)	16 cal./g 29 b.t.u./lb.
Total Heat Available from Sublimation to 0°C	152.9 cal./g 275.4 b.t.u./lb.

odorized gas is then compressed and condensed to liquid.

Natural gases may be similarly purified by the treatment with adsorbents and solvents to remove their impurities (usually hydrocarbons) prior to final liquefaction.

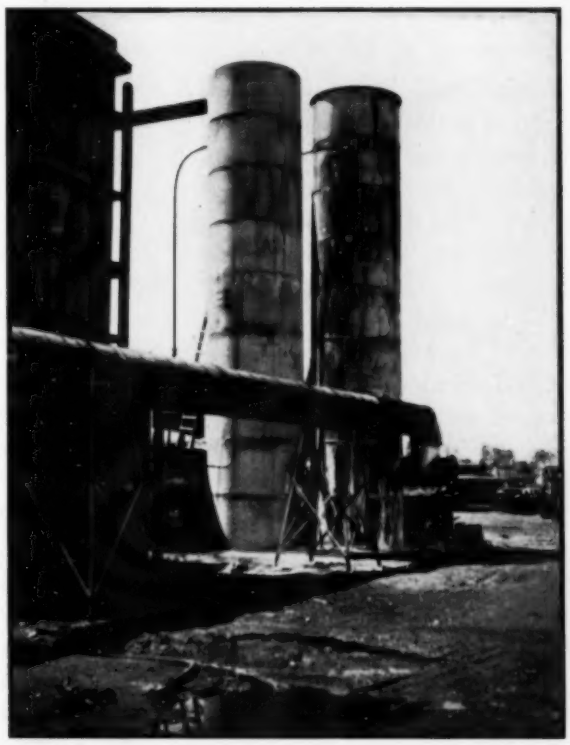
These processes are relatively simple and inexpensive when compared with the concentration of carbon dioxide from dilute mixtures, such as flue gas. Concentration of these is effected by taking advantage of the greater chemical reactivity and solubility of carbon dioxide as compared with nitrogen by forming loosely bound chemical compounds with alkaline materials. These are subsequently decomposed to yield pure carbon dioxide. Practice in this operation has been recently reviewed in considerable detail by Martin and Killeffer[2] and for present purposes will be briefly sketched as applied to flue gas.

For economical operation, the carbon dioxide content of the flue gas must be as great as possible. The limit is 20 percent carbon dioxide, unless enriched as in lime kiln operation where 35 to 40 percent is common. In commercial practice, coke is burned as fuel under power boilers to yield gas of 17 to 18 percent carbon dioxide in the flue. The power produced is used in the subsequent operations and the gas, washed free of sulfur dioxide and fly ash, is passed to the absorber towers. There it is brought into intimate contact with a solution of an alkali. The alkalies used are sodium carbonate, potassium carbonate and various organic amines. Contact is secured by passing gas up through the absorber down which the lye solution flows on a suitable packing material, coke or steel turnings. The reaction which occurs may be represented as follows:

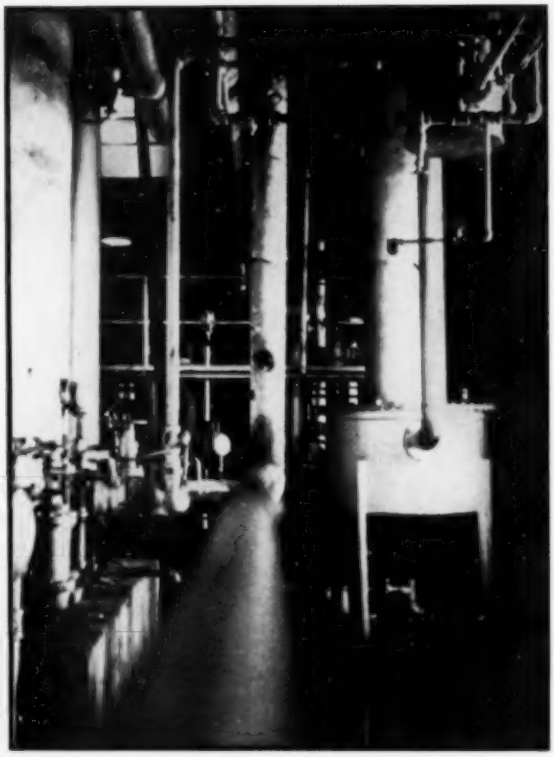
$$K_2CO_3+H_2O+CO_2\rightleftharpoons 2KHCO_3.$$

In the absorbers this reaction progresses to the right. After absorption, the lye is pumped to a boiler in which it is heated to the point where the direction of the reaction is reversed and carbon dioxide mixed with steam is evolved. The steam is readily condensed by cooling, leaving very pure carbon dioxide. The expense of the process lies in the large quantity of steam evolved with the gas (from 6 to 7 pounds per pound of carbon dioxide) and in the fact that only part of the carbon dioxide originally present in the flue gas can be absorbed. Numerous methods—some have been successful—have been proposed to allow the more complete stripping of the flue gas (Martin and Killeffer, reference 2). Also purely physical methods of separation by imposing pressures great enough to liquefy carbon dioxide from the flue gas cooled to a low temperature have been considered. In any case the separation of carbon dioxide from dilute mixtures is sufficiently costly to make other more concentrated sources especially useful.

Once the gas is separated in pure form, its liquefaction is accomplished by compression and cooling. For economy's sake, 3-stage compressors are used with interstage coolers and moisture condensed by compression is bled off after each cooling. The pressure is ultimately raised above about 70 atmospheres (determined by the temperature of cooling water available) and the gas is liquefied. Final moisture may be bled oft from the liquid reservoir or chemical driers may be used.



Sulfur dioxide is washed out of flue gas in concrete towers with alkali solution. Plant of International Carbo-Ice, Ltd., Toronto.



Lye boiler (left). Atmospheric condenser on steam engine exhaust (right). International Carbo-Ice, Ltd., Toronto.

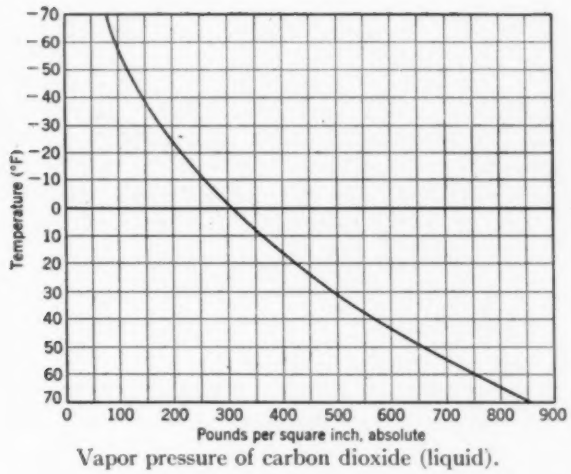
This liquid is the commercial product marketed in cylinders or it may be the raw material for solidification. If it is to be solidified, the next step is to cool it further and finally by its own evaporation, to solidify part of it.

Differences of opinion exist as to the most economical method of converting liquid at, say, 20°C to solid at −78.5°C, and the subject is covered by an intricate network of patents not yet adjudicated by the courts. In any case the over-all result is the same, the methods used differing in power consumption to an extent which becomes more important the larger the scale of the operation. The entire cooling may be accomplished by an external refrigerating system, part of it may be done externally and part by the evaporation of carbon dioxide, or all of it may be done in a self-cooling cycle in which carbon dioxide is the refrigerant. In the first process, difficulties with refrigerants to cover the required range and with heat transfer to the carbon dioxide are encountered which have prevented its commercial success. In the last, the low latent heat and relatively high specific heat of carbon dioxide at high temperatures require the handling of immense volumes of gas to do an effective cooling job. Despite this drawback, direct evaporation of liquid to solid with the use of the evolved gas to precool liquid before expansion was for several years the only practice in the industry, and with modifications it is still the principal one. The second method has much to recommend it in saving power, and especially where cooling water temperatures are too high for the use of carbon dioxide refrigeration alone, is often employed.

The advantage of using a supplementary refrigerating system in connection with the liquefaction and solidification of carbon dioxide lies in the fact that in the range from the critical point of carbon dioxide down to about −10°C the efficiency of ammonia systems is relatively much higher than that of carbon dioxide machines. By cooling the gas after compression to such a temperature the pressure required for liquefaction is materially reduced and with it the load on the carbon dioxide compressors. At −10°C, for instance, liquefying pressure is less than 400 pounds per square inch as compared with more than 850 pounds at +20°C. Another important advantage is secured through the reduction in the specific heat of the liquid and an increase in its latent heat by this reduction of temperature.

When the cooling is entirely accomplished by the carbon dioxide itself, a method preferred by many operators, there is no loss of refrigeration and no impedance to heat transfer since the evaporation of the liquid itself does the actual cooling. To take advantage of this, systems are designed to perform the evaporation of the liquid in stages with recompression of the gas separately from each stage. Normally these are adjusted to fit the stages of the compressor, the first expansion carrying the liquid to about 300 pounds and the second to 75 to 90 pounds. In this way a substantial reduction in the power requirement is attained.

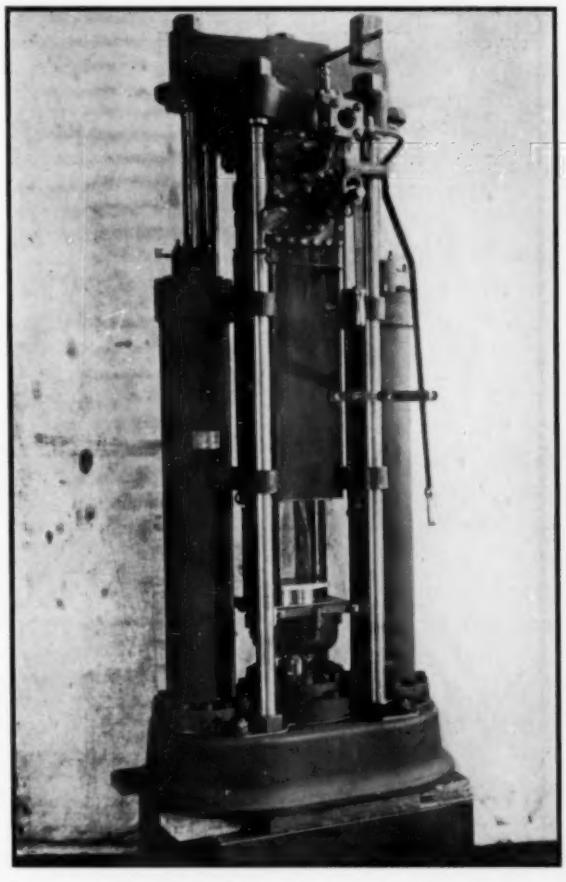
In any case the temperature of the liquid cannot be reduced below that at triple point −56.6°C since at that temperature it will solidify. In practice, liquid is cooled to a point near but above the triple point and then is



Vapor pressure of carbon dioxide (liquid).

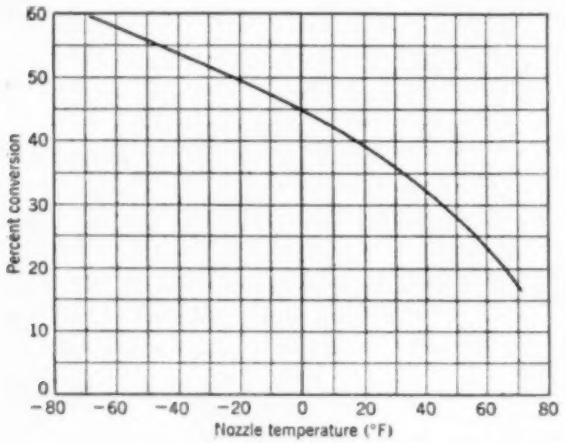
allowed to evaporate to solidify partly, the gas formed being recompressed from the triple point pressure (5 atmospheres—75 pounds absolute). The preferred modern practice is based on the formation of the larger part of the prospective block of solid as snow, wetting this with liquid and finally permitting the whole block to solidify by evaporation of the residual liquid at the triple point. This provides, after pressing with a hydraulic ram, a denser block than can be obtained if dry snow is compressed directly. After the block is formed and pressed, the pressure on it is reduced to one atmosphere to permit it to cool off to the subliming temperature before removal from the press. This contrasts to the old method in which liquid expanded through a nozzle from a pressure up to 1000 pounds per square inch directly to one of approximately 10 pounds per square inch. The older process formed dry snow which was pressed into blocks by hydraulic pressure. The blocks themselves when thus formed are relatively fragile and hence this method has been abandoned in favor of the wet snow method in order to secure a sturdier block which can be more readily handled.

In present practice the blocks of solid carbon dioxide as formed are usually $20'' \times 20'' \times 10''$ and from these, standard 10-inch cubes weighing approximately 50 pounds each are cut with a band saw. The finished blocks are individually wrapped in paper and are ready for shipment or use. At each stage in the evaporation of the liquid the gas produced is returned to the compression system at the pressure of its formation in order to minimize the work required for its reliquefaction. The yield of solid from liquid is a definite function of the liquid's temperature. If self-cooling is employed, then the temperature to be considered is that from which self-cooling begins. If the liquid enters the system at 15°C, 24 percent is converted to solid by processes of self-cooling. At 10°C the percentage solidified rises to 28. If on the other hand, liquid is supplied to the system at −18°C the conversion is approximately 45 percent. In any case, the difference between the original mass of liquid and the quantity of solid produced is vaporized, and it must be recompressed for reliquefaction. This, of course, does not mean that the unconverted gas is lost but rather that it requires more work to be done on it for conversion to solid.



Press for making solid carbon dioxide. Press is now in open position. Lower platen is forced against opening of chamber by hydraulic pressure and ram inside chamber compresses solid carbon dioxide when formed into blocks for use. Controls allow expansion of liquid into chamber at any pressure and on any cycle desired. Courtesy York Ice Machinery Co.

The uses of solid carbon dioxide are naturally inherent in its properties already outlined. Approximately 85 percent of present production in the United States is used as a refrigerant.

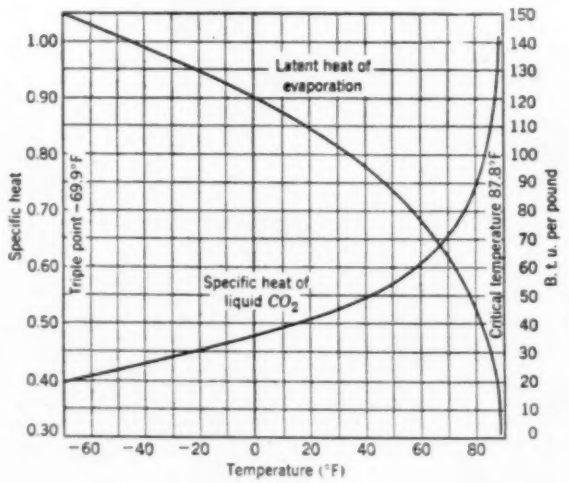


Conversion of liquid CO_2 to solid at different nozzle temperatures.

Most of this (69 percent of the total) is consumed in the refrigeration of ice cream, principally in trucks and transportation packages. Refrigeration of meat and fish in trucks and to a smaller extent in railroad cars accounts for another 12 percent. The relatively new industry of frozen foods and other refrigeration tasks make up the remaining 4 percent. Approximately 10 percent of the total production in the United States is consumed in industrial uses of which the most important are: the production of atmospheres of pure dry carbon dioxide for chemical or other purposes; as a substitute for liquid air in condensation traps of high vacuum systems; in preventing the self-hardening of aluminum alloy parts, particularly rivets, after heat treatment; in cooling cores for shrink fits; and in the finishing of molded rubber articles from which the mold fins can be readily broken when cooled to dry ice temperatures. Approximately 5 percent of the solid produced in this country provides a convenient method for supplying liquid at the point of use where it is melted under pressure.

In its use in refrigeration the preservative action of the gas evolved on meat and fish is a particular advantage. Cut flowers are also benefited by the gas if its concentration is not allowed to rise to too high a point for too long a period. Eggs in cold storage are maintained in a fresh condition for a much longer period if the atmosphere of the storage space is supplied with regulated amounts of carbon.

Despite its advantages, the use of dry ice as a refrigerant seems likely to be limited by its cost. In mobile refrigeration the weight reduction it makes possible yields a supplementary return great enough to offset the higher cost of cooling effect in this form. Where extremely low temperatures are needed, it has a cost advantage over most refrigeration systems. The cost of solid carbon dioxide is of the order of 10 times that of water ice in large wholesale quantities, yet it produces only about twice as much refrigerative effect. Although this difference in cost may be considerably reduced in the future, it seems unlikely that the cost of cooling effect in the two materials will ever reach a par. Improved methods of application may possibly widen the field of use of dry ice by increasing its efficiency. Costs may also be lowered by improved methods of manufacture and particularly by the use of



extremely cheap off-peak or incremental power. On the other hand, low temperature refrigeration of loads in transit will continue for some time to come to be the mainstay of the industry as it has been in the past.

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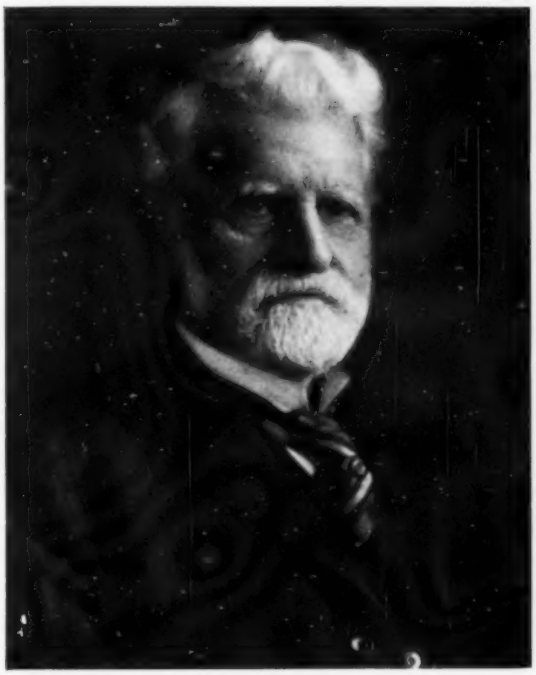
Ambrose Swasey Builder of Machines, Telescopes and Men

By J. J. NASSAU

"You know, it wasn't so long ago since Galileo was put into prison for saying that the world was round and that the sun was the center of the Universe," once said Ambrose Swasey. "That was not so very much before my time, only one hundred and twenty-five years before the birth of my grandfather whom I remember well. People now do not know much more than they did then." And yet people do know more on account of Ambrose Swasey for he built giant telescopes that pierced the depths of space and devoted his talents to science and engineering, leaving a lasting influence upon his age. On June 15, 1937, he died, a great task completed, four score and ten years of noble living.

Childhood

THE Swasey family have been residents of New England since 1686. They immigrated to this country from England. Ambrose was born on December 19, 1846, the son of Nathaniel and Abagail Peavey Swasey and was the ninth of ten children. Nathaniel Swasey, a progressive farmer of Exeter, New Hampshire, was sufficiently skilled in the mechanical arts to make his own tools and wagons, and young Ambrose must have learned to do things with his hands on the farm. The study of ancient history and astronomy occupied the intelligent interest of this New England farmer. From his father Ambrose doubtless got his trait of intellectual curiosity. From his mother he inherited his cheerful disposition and his vein of quiet humor with which for years he delighted his associates.



There were no mechanical toys when Ambrose was very young but he soon learned to make his own. Mother's old spinning wheel and his jackknife helped in making a flax wheel. The old attic was his workshop and there he set up an improvised lathe. Then he made a working model of a mowing machine which is still in existence. Boys on old New England farms all had duties and Ambrose was in charge of the sheep and lambs which he loved and gently cared for. When Eben, his next older brother and close companion, was in college, young Ambrose took him to school every Monday morning and called for him on Friday afternoon, often driving through heavy snow drifts.

The brothers got into their share of difficulties. When Abraham Lincoln went to Exeter to visit his son Robert who was attending the Academy, Eben and Ambrose thought it fitting to celebrate this unusual event by building a bonfire. This they did on a hill back of their house and nearly succeeded in burning the old homestead.

Apprentice—Meeting W. R. Warner

"Although all my brothers and sisters went to academies or colleges, my only schooling came from the little country grammar school and lasted only two or three months," said Swasey. But he received half a dozen degrees from leading Universities, helped to shape higher education in America and led in the development of scientific and engineering research.

He made his final decision upon a career in 1865 when he told his father he would like to learn the machinist's trade. Up to that time the hope of the family was that he would follow his brothers and sisters to some institution of higher learning. But he went to a newly established machine shop in Exeter. A year later, another young man of the same age and as eager to learn as Ambrose came from Boston and started to work in the same shop. This young man was Worcester R. Warner. The two enthusiasts soon became warm friends.

As Ambrose started ahead of Worcester in the apprentice work, he finished first, and then to widen his experience he went to Paterson, N. J., to enter the employ of a locomotive firm. He soon found the work unsuited to his inclinations and perhaps, too, a bit of homesickness hastened his return to Exeter. Once again the two young friends spent the winter working together in the shop, living and studying together, and planning for the future. This was the development period of two astonishingly parallel characters, not in any sense identical but rather, complementary.

It may be said that the spring of 1869 marked the beginning of their life long partnership, for at that time they wrote letters to four companies seeking positions as machinists. The result was four offers. As was to be expected they made the same choice. After their first day's work at the Pratt and Whitney shops in Hartford, Connecticut, Warner remarked to Swasey, "Well, Ambrose, we have a very difficult job. There are three hundred young men ahead of us." But soon they attracted attention by their special abilities in solving mechanical problems, and the number ahead of them diminished, for both were given important positions which they held until they left the employ of the company eleven years later to start out independently to establish a business of their own.

Cornell Offer

The training he received on his father's farm, the experience he gained in the Exeter machine shop where men found joy in good workmanship, the long hours spent in his room at night studying books on machines, all showed their first fruits soon after Ambrose Swasey joined Pratt and Whitney. At thirty-two, he was made superintendent of the gear cutting department. A year later, through study and development at his home nights, he produced a beautiful piece of mechanism, the epicycloidal gear engine. It was constructed in the shop under his direct supervision and proved to be a success. His inventive ability, his breadth of knowledge both theoretical and practical must have been recognized beyond the limits of this New England shop, for in 1879 he was invited to succeed John E. Sweet, professor of Practical Mechanics at Cornell University. The invitation surprised him. He underestimated his ability, self-training, and experience and he declined the offer.

First Patent

Being in charge of the gear making department was not sufficient occupation for the energetic mind of the young machinist. He found time to invent and obtain a patent for an improved protractor, an instrument for laying and measuring angles with great exactness. It is significant that his first patent was in that direction, for mechanical accuracy became one of the major factors in his great success as well as a deeply rooted phase in his character. He commenced early in his career to pay special attention to the subject of gearing. Besides the epicycloidal milling machine, he invented a new gear cutting machine for generating and at the same time cutting the teeth of the spur gears. Many other patents followed, the majority of them for turret

machines and optical sighting instruments. Today an important division of Mr. Swasey's achievements is the design of military instruments of precision, including the invention of the depression Position Finder for seacoast defense fortifications, used by the United States Government for a number of years.

In his scientific writings one may easily see his profound understanding of the evolution of thought in mechanical engineering as well as astronomical technique.

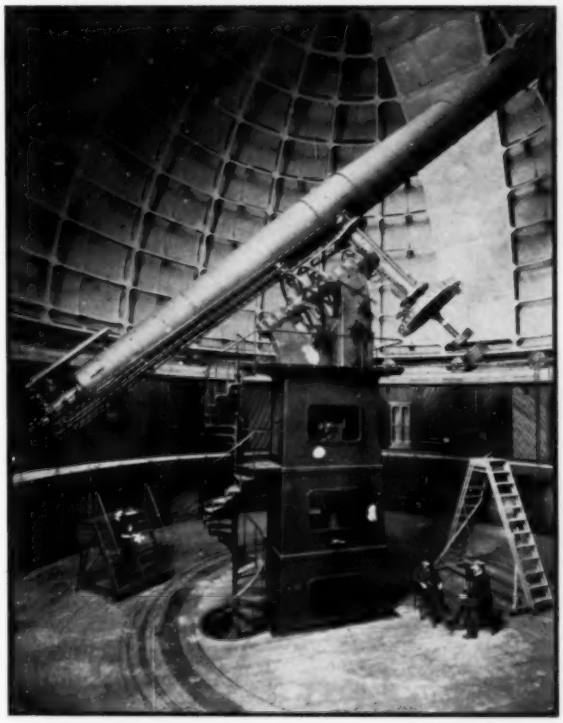
The Cleveland Firm

In 1880 Warner and Swasey left Hartford to enter business for themselves having for capital, eleven years of joint savings. Their first location was in Chicago, but later they felt this was too far removed from the industrial east, and they decided to move. On July 8, 1881, there came to Cleveland a new citizen, a young man with a striking face, beaming eyes and the picture of health, Ambrose Swasey, the machine tool builder. His partner had left Chicago some months earlier to supervise the construction of the shop they had planned for this city.

There was little difficulty in obtaining orders and the new firm concentrated on a policy of establishing the highest standards in their products, whether in machine tools, instruments of precision, or telescopes. The two men were so absorbed in the designing and making of machines, and the trust in each other was so great that they did not bother to draw up a written agreement of partnership until 1900 when they incorporated as the Warner and Swasey Company.

Early Astronomical Work

Astronomy had been the delight of Worcester Warner since early youth. His interest inspired his young friend Ambrose and soon this subject became an added bond between them. They had talked and thought and built small instruments for many years. It is not difficult therefore to understand that soon after they had established themselves in business, they had designed a distinctly improved mounting. This first telescope, a nine and one-half inch refractor, was sold to Beloit College upon the recommendation of Professor Burnham. A year later in 1882, they



An early photograph of the Lick telescope showing Professor Keeler (on the observing chair), Mr. Swasey, and Captain Floyd.

constructed their first big dome, forty-five feet feet in diameter, for the Leander McCormick Observatory of the University of Virginia.

The tremendous progress in telescope making may be realized when we recall that the largest telescope in the world in 1845 was a fifteen-inch refractor. Harvard College and Pulkowa each shared the honor of such a telescope. The race for larger instruments may be said to have commenced about that time. The two young partners had much to do in bringing America to its undisputed supremacy.

Lick Telescope

When the Lick trustees were preparing for the largest and most powerful telescope in the world, according to the wishes of James Lick, plans and bids were asked for the mechanical parts from all the telescope makers of the world. This was taken as a challenge by the two visionary and energetic manufacturers. Their knowledge of astronomy was limited and their experience in telescope making went not further than the nine and a half inch instrument for Beloit College. This new venture was a problem of the first

Mr. Swasey on his eighty-ninth birthday, with the eighty-two inch MacDonald telescope mounted in their shops.

magnitude even for the most experienced engineers in this field. The undertaking called for an instrument to be used not only for visual work but photographic and spectroscopic as well, new functions at that time. With their characteristic thoroughness and team work, the two partners in a few months submitted plans and theirs was the highest bid submitted. The design in which they included for the first time polar and declination axes of steel, ball bearings, and improved counterbalancing was judged to be the best, and it received the award.

On November 14, 1887, a year and a half later, Mr. Swasey left Cleveland for California to supervise the erection of this magnificent instrument. On December 31, Alvan Clark placed his masterpiece, the thirty-six inch objective, in the tube of the telescope. The astronomical career of the Lick telescope began on January 3, 1888, when Captain R. S. Floyd, president of the Lick trustees, Alvan Clark, J. E. Keeler, and Swasey observed through it, first Aldebaran and later the Great Nebula in Orion.

Period of Large Telescopes

Soon after the completion of the Lick telescope came the building of the new mounting for the twenty-six inch refractor and the meridian circle for the United States Naval Observatory.

When in 1892 the forty-inch Yerkes was projected there was no doubt as to the style of mounting, nor as to the makers. They received the contract for the telescope and the ninety foot dome without competition. The result was this world famous instrument which combines beauty and precision, strength and delicacy of motion, characteristics close to the heart of its designer.

The trend in astrophysics, particularly at the beginning of the century, brought reflecting telescopes into great prominence and Ambrose Swasey took an active part in their design and construction. It was his engineering genius that made possible the improvement in the mounting of the secondary mirrors which enables one to change from the Newtonian to the Cassegrain arrangement with little danger or loss of time. This was first done for the seventy-two inch reflector of the Dominion Astrophysical Observatory.

The completion of the mounting for the eighty-two inch MacDonald telescope coincided with his eighty-ninth birthday and it was very evident at that time that he was proud to see that the men whose skill he had helped develop were doing such creditable work.

For over eighty years the work of the construction of large telescopes and the figuring of their optical parts has been done in America. The only non-American feature which astronomers in this country needed was the glass from which lenses and mirrors are made. Ambrose Swasey felt that the United States should be able to make such glass at least for large mirrors and spoke to Herbert Hoover, then Secretary of Commerce. He suggested that the Bureau of Standards might undertake to furnish a sixty-inch disk for the Perkins reflector. After a number of unsuccessful trials, the Bureau finally produced in 1923, a sixty-nine inch disk, the first large disk made in America.

Dividing Engine

Last May Mr. Swasey was asked, "What in your opinion is the greatest thing you have done?" All at once his eyes sparkled, his face

brightened more than ever, and it seemed that a war veteran was getting ready to describe a famous battle. "The highest type of construction and piece of work I ever did," he said, "was the dividing engine. When you can take a spindle four inches in diameter and about twenty-five inches long with five-eighths inch taper to the foot and make that spindle fit into a bearing easily and when you drop it a thousandth of an inch it goes hard, you are getting down to a refinement about which we knew nothing in those times. Dividing engines had all fallen down on the spindle—could not get a spindle in the bearing that would fit." The dividing engine was built primarily for graduating circles of astronomical instruments used for fundamental star work as well as for instruments in geodetic surveying. It has an error of closure of one second of arc and required three years in building. It was fortunate that during this period Mr. Swasey had with him the most able assistance of Mr. G. Fecker the talented optical expert.

The joy of working for and attaining accuracy in machines was an inborn characteristic as it is in many of our greatest scientists. To construct a machine as accurately as is humanly possible to do and to make it durable, beautiful and practical was the motive power of his great career. This aim is evident in all he has done, in planning a building for some college campus, in the establishment of a Foundation or in building a telescope.

Engineering Foundation

Mr. Swasey has taken an active part in the foundation of the American Society of Mechanical Engineers and in 1904 served as its president. His interest, however, extended to other engineering and scientific societies.

His association with scientists and engineers strengthened his belief in the value of research to engineers and industry and at the same time, he perceived that its importance was not sufficiently apprehended. Realizing the need, he conceived, and in 1914 established the Engineering Foundation for the furtherance of research in science and engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind. This was the first known instance of a Foundation devoted primarily to engineering purposes. His gift amounting to three-quarters of a million dollars has contributed in many ways to the advancement of the profession which was so dear to him and made possible the initial organization of the National Research Council. The activities of the Foundation were wisely and broadly planned, to be readily adaptable to the varying needs of the profession. The Foundation well expresses the deep interest of Mr. Swasey in things which upbuild and endure.

Mr. Swasey with the dividing engine which in his opinion was his greatest engineering achievement.

The Builder of Men

We need but contemplate the fine machines and astronomical instruments which his firm built to realize that Mr. Swasey's inventive and mechanical genius as well as his love of precision and artistic design contributed greatly to his successful career. He was able to recognize greatness and nobility in men and to choose his friends wisely; they enriched his life as he enriched theirs. We find among his astronomical friends

such men as John A. Brashear, Alvan Clark, Simon Newcomb, Asaph Hall, Edward Pickering, C. A. Young, J. E. Keeler, S. W. Burnham, and E. E. Barnard. "These men stand out as first magnitude stars in the realm of astronomical science, and to have had some part in their great work for science and humanity is indeed glory enough and compensation enough."

Another factor which contributed to his success was his ability to select capable young men and systematically to train them. He and his partner were among the pioneers in establishing an apprentice school which goes as far back as 1880. "They call this the age of metals and machinery," Mr. Swasey used to say, "but the time will never come when the world will not need fine men more than it needs fine machinery." Toward this need he worked as assiduously as he did in building machines and telescopes.

Honors

It was but natural that he should be the recipient of many honors both at home and abroad. He held six honorary degrees, and membership in many engineering and scientific societies, including the National Academy of Sciences and the American Philosophical Society. He was a Fellow of the Royal Astronomical Society and Officier of the Legion of Honor (France). He was awarded numerous medals. In 1924, in recognition of his many contributions to the development and progress of engineering, Mr. Swasey received the John Fritz Gold Medal, the highest honor bestowed by the engineering profession in this country. In 1932, he was awarded the Franklin Gold Medal by the Franklin Institute in recognition of his development of methods and his invention of appliances for making machines, instruments of precision and mountings for large telescopes.

He deeply appreciated the honors he received and in a way enjoyed the ceremonies which were inevitable upon such occasions, although he accepted them with respect and modesty. He wished to say, "It is a great privilege to be counted among the distinguished men of science whom you have already honored. I thank you for the joy that you have so graciously given me."

The following short narrative illustrates his modesty. When once Mr. W. H. Croker of San Francisco remarked, "Why, Mr. Swasey, you are an astronomer." He replied, "When I was a boy, my father kept a great number of sheep and when working around the barn and with the sheep, some of the wool rubbed off on me, but that didn't make a sheep of me. In later years, I have been working with scientists and astronomers and rubbing up against them, but it takes more than that to make an astronomer."

It was a source of great pleasure to Mr. Swasey when on his eighty-eighth birthday, Dr. Otto Struve announced the naming of Asteroid 922, "Swaseya." Dr. Struve's discovery of the asteroid was made on November 14, 1922.

Private Life

Mr. Swasey was married in 1871 to Lavinia Marston who came from his own New England state of New Hampshire. She was reserved, gracious, and deeply religious, much like her husband. At their home in Cleveland, they lived quietly with but little entertaining which was mostly restricted to out of town guests. There were no children. Mrs. Swasey died in 1913.

He traveled extensively at home and abroad, went around the world twice, and in 1917 for the third time visited China where for many years he had been interested in the collection of old coins and in promoting higher education. As an expression of his deep interest in Chinese education he provided funds for the erection of the Canton Christian College Y. M. C. A. building and the Science Hall at Nanking University.

His life long interest in architecture and his love for the beautiful contributed materially to the architectural design of many college buildings for the erection of which he gave the funds.

His interest in engineering and research, in higher education, and in the Baptist church are well expressed by his generous contributions.—"Whatever success I have had," he used to say, "which enabled me to make these gifts, I owe not to myself but to the fact that I have had a good mother, a good wife, and a good partner in business."

His unusually robust constitution kept him active until the end. Only last summer he paid a short visit to his friends in England. On the occasion of the presentation of the Hoover

Medal in December last, he took his full share in the ceremony, including a short speech of acceptance. In April he attended the meeting of the National Academy of Sciences in Washington.

On May 21st, a cold confined him to his Cleveland home but his strength was now rapidly failing in spite of his great will to live. On June 9th, upon his insistent request, he was taken to his native home in Exeter. The end came a week later.

His active life covered nearly three-quarters of a century. His achievements in his chosen field and his influence for good have made us all the richer. We may well rejoice that his noble life coincided with part of ours.

Case School of Applied Science,
June 24, 1937.

The importance of advanced education for leadership in business is indicated by a recent survey reported to the Society for the Promotion of Engineering Education, which showed that out of 15,084 college-educated officers of American industry, including presidents, treasurers, and executives in engineering, sales and production, 12,225 were graduates of engineering and scientific institutions, and 2,859 from all other types of colleges. Of the 235 college-trained presidents in American industry, 151 were educated in technical and 84 in other educational institutions.

KARL T. COMPTON

Design of a Million-Volt X-Ray Generator for Cancer Treatment and Research

By J. G. TRUMP AND R. J. VAN DE GRAAFF
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Cambridge, Massachusetts

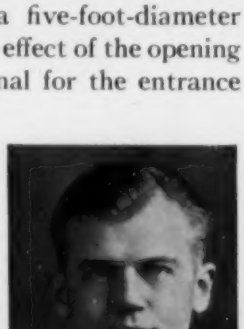
A MILLION-VOLT x-ray generator for cancer treatment and research has been developed by the Massachusetts Institute of Technology and is now in use at the Huntington Memorial Hospital of the Harvard Medical School in Boston. The experimental construction of this x-ray generator was undertaken to meet the needs of the medical profession for a relatively simple, compact and intense source of penetrating radiation. The general arrangement of generator and tube is shown in Fig. 1.

High Voltage Source

The high voltage source is a direct-current electrostatic generator of the belt type.[1, 2] This generator is essentially a belt conveyor of electricity, electric charge being transferred between a high voltage terminal and ground at a uniform rate by rapidly-moving belts of insulating material. The terminal has maximum dimensions of 13 ft. by 15 ft. by 5 ft. high and is made of $\frac{1}{8}''$ aluminum sheet supported on a rectangular steel frame. The surfaces are smooth and well rounded to avoid corona at high voltage, the top surface being flat, the sides cylindrical, and the corners quadrants of a five-foot-diameter sphere. To avoid the adverse effect of the opening at the bottom of the terminal for the entrance of the belts and of the x-ray tube this bottom surface has been made re-entrant to a depth of about 18 inches. This re-entrancy reduces the voltage gradient in the vicinity of the opening and materially improves the insulation strength in this region.

The high voltage terminal rests on a rectangular insulating column 10 ft. in height, made of four cross-braced wax-impregnated mahogany corner posts. The belts run inside this column which is enclosed by ceresined Masonite and kept warm internally, thus eliminating the effects of humidity and rendering the operation of the generator independent of weather conditions. Six commercial four-ply fabric belts, each 3 ft. wide, travel between the lower grounded pulleys and the corresponding pulleys 12 ft. above within the high voltage terminal. These belts run at a speed which can be varied from 4,000 to 5,000 ft. a minute, the ascending runs of belt carrying negative charge to the high voltage terminal, and the descending runs carrying away positive charge. The six lower pulleys are driven in pairs by three $7\frac{1}{2}$ h.p. 1800 r.p.m. d.c. motors.

Negative electric charge is sprayed on the belts at the lower grounded end of belt travel from rows of corona points directed at the pulleys. The necessary high voltage current for this purpose is supplied by a 250-watt, 20-kilovolt transformer rectifier set within the base. In a similar manner, within the high voltage terminal the negative charge brought up is neutralized and positive charge sprayed on the descending run of belt by means of corona points. The similar 20-kilovolt transformer rectifier set for the upper corona points is supplied with power from a 500-watt alternator driven from below by an insulating belt. The charge carried by the belts is controlled by simultaneously regulating the upper and lower transformer-rectifier voltages from the control board.



R. J. VAN DE GRAAFF

J. G. TRUMP

The generator operates normally at a steady

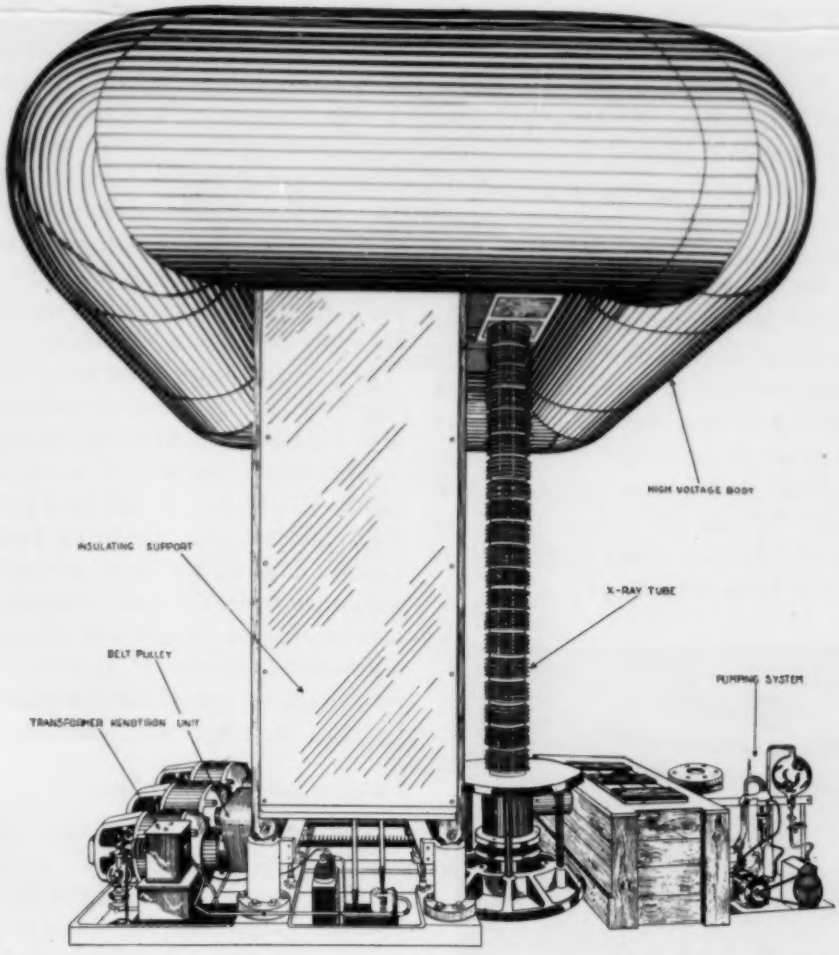


FIG. 1. General arrangement of the million-volt x-ray generator and tube. The bottom cover is shown removed.

value of one million volts and can deliver three milliamperes of current on the x-ray target at this voltage. Stable operation can be had at all voltages from 500 kilovolts to 1,200 kilovolts. The voltage of the generator may be read on a microammeter at the control panel as the current through a calibrated high resistance. A resistor for this purpose was constructed by Dr. L. C. Van Atta and Mr. D. L. Northrup using a technique developed by them at the M. I. T. laboratory at Round Hill and to be described by them in a subsequent publication.

Million-Volt X-Ray Tube

The x-ray tube shown in Fig. 2 is of the cascade type[3, 4] and consists of twenty porcelain sections mounted vertically, the voltage being distributed equally between sections by means of corona. These porcelain sections are corrugated inside and outside to increase the creepage path, and have an external diameter of about 12″. All the vacuum-tight seals between sections are made with endless gaskets of $\frac{3}{32}$″ lead wire, on which a total spring maintained compressive force of about 6 tons is exerted and to which glyptal has been applied on the outside. The porcelain stack is 10 ft. high and is mounted on a steel flange supported from the floor of the equipment room. A grounded steel tube continues on axially from this flange passing through the floor and into the treatment room below where it terminates in a water-cooled lead target. Within the treatment room this steel tube extension of the x-ray tube is 3 inches in diameter and is lead-shielded, the thickness of the lead increasing to three inches in the neighborhood of the target.

Electrons are emitted from a 12-mil filament at the upper end of the tube, directed in a parallel beam by an electron gun of special design, and kept focused by electrostatic lenses between each porcelain cylinder. As shown in Fig. 3, the electron gun is mounted with a copper bellows arrangement to permit its movement about the axis of the tube. This enabled the position of the electron gun to be adjusted initially until the total spot was accurately centered on the target. During this initial adjustment the position and size of the focal spot was observed visually by the fluorescence on a quartz disk inserted in place of the target. The position and size of the focal spot is now easily checked whenever desired by use of a lead pin hole camera. Very little shifting of the spot position occurs over a wide range of voltage.

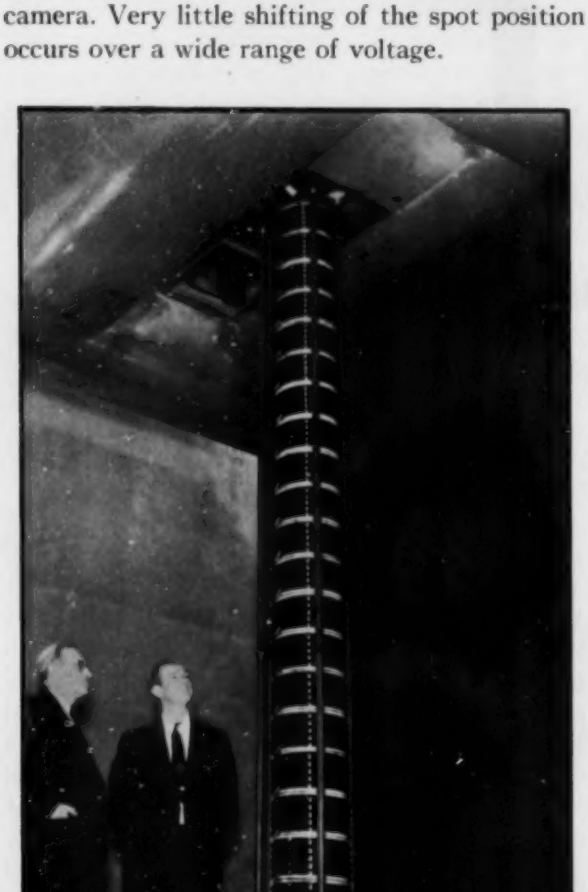


FIG. 2. Cascade type x-ray tube.

The electrons impinge on the water-cooled lead target 16 ft. under the filament in a circular focal spot which, without magnetic focusing, is $\frac{7}{8}$-inch in diameter at a million volts. A magnetic coil[5] of about 2,000 turns, located 4 ft. above the target, has been provided to reduce the size of this focal spot. The current in this focusing coil is ordinarily left at $\frac{1}{2}$ ampere, resulting in a focal spot $\frac{3}{4}$-inch in diameter. The focal spot may be reduced to $\frac{1}{2}$-inch diameter by passing 1 ampere through the coil and to about $\frac{1}{8}''$ by $1\frac{1}{2}$ ampere. The current through the x-ray tube is controlled by regulating the filament temperature by means of a Variac operated from the control panel.

The target consists of a copper cup on the inside of which a 15-mil lead coating[6] has been electroplated, the cup being cooled by a water jacket. The target is at ground potential but insulated from the tube extension, so that the current to the target can be read on a milliammeter at the control panel. The x-rays utilized in treatment are those transmitted downward through the target and water-cooling jacket.

Continuous Pumping System

The x-ray tube is continuously pumped by means of a two-stage mercury-vapor diffusion pumping system backed by a Hyvac fore pump. The maximum pumping speed developed by this system is somewhat greater than 100 liters per second at the x-ray tube. A CO_2 trap of special design with a capacity of 150 lbs. sufficient for one week has been provided to prevent the mercury vapor from reaching the tube. The x-ray tube can be exhausted from atmosphere to an insulating vacuum in half an hour, and used without any preliminary outgassing. An equilibrium pressure of about 2×10^{-6} mm Hg is normally maintained in the tube. This provides a margin of at least a factor of 10 in the pressure required for insulation. A thermocouple gauge, an ionization gauge, and a McLeod gauge are available for pressure measurements.

Housing

The apparatus has been erected in an addition to the main hospital building. The equipment room has inside dimensions of 23 ft. by 25 ft. by $20\frac{1}{2}$ ft. high, the walls and ceiling being lined with sheet metal. The treatment room shown in

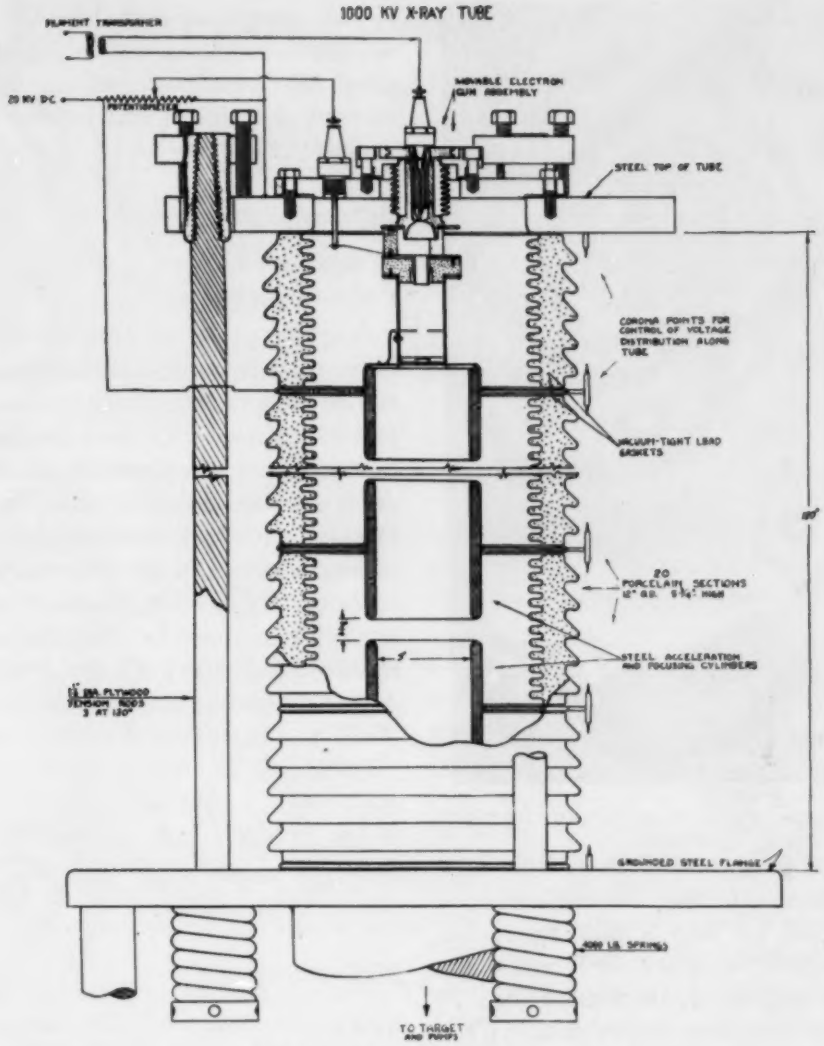


FIG. 3. Electron gun and tube.

Fig. 4 is under the equipment room and below ground level, and is 12 ft. by 17 ft. by 8 ft. high. It is completely free from high voltage apparatus and special attention has been given to making this room a pleasant one. The arrangement of the target at ground potential permits various treatment distances down to a minimum of about 15 centimeters.

Operation

All the necessary operations in starting and controlling the generator are performed at the control panel. The instruments required for observing the performance of the generator and for measuring the vacuum are mounted on this control panel which is located adjacent to both treatment and equipment rooms. The procedures in operating the generator are exceedingly simple and can be quickly learned by the average technician. The generator may be left at a predetermined voltage and current setting, and full voltage and current applied in about a second without injury to the tube. The total power input to the x-ray generator, inclusive of all auxiliaries, when operating at full load is about 15 kilowatts.

X-Ray Output

Ionization measurements with a thimble chamber of standard design give 40 roentgen units per minute per milliampere of target current at one million volts at 80 centimeters with 6 mm

FIG. 4. Treatment room which is completely free from high voltage apparatus.

of lead equivalent filtration. Operation at a reduced current of 1.0 to 1.5 milliampere has been found desirable in order to increase the average treatment time to between 5 and 10 minutes. The 10-centimeter depth dose with a 10 cm×10 cm field at 80 centimeters' treatment distance and with the above filtration was found to be 51 percent. Preliminary measurements of the one-half layer value of copper give 10.5 millimeters. These measurements were made by Drs. Richard Dresser and Jack Spencer of the Huntington Memorial Hospital staff, who are in charge of the apparatus.[7]

The generator has been in operation for several months, has shown reliability and economy in operation, and provides a precisely controlled source of very intense and penetrating radiation.

Acknowledgments

Acknowledgments are made to the Research Corporation for its support of the M. I. T. high voltage program, to members of the M. I. T. high voltage group at Round Hill for their advice and cooperation; to Mr. Frank Scholz and Mr. Bernard Cosman for their work on the assembly; to Mr. Reed Maull for development work on the electron gun; to Drs. Richard Dresser and Jack Spencer for their intensity measurements and for their encouragement and support; and to Dr. Joseph C. Aub, Director of the Department of Medicine of the Huntington Hospital, for his interest and cooperation. Acknowledgment is due to the Permanent Science Fund for the grant which made possible the construction of the resistor used for voltage measurement, and especially to the Godfrey M. Hyams Trust whose generous grant made possible the construction and installation of the new x-ray generator.

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Discoveries and inventions are not terminals; they are fresh starting points from which we can climb to new knowledge. WILLIS R. WHITNEY

Some Problems of Physics in the Application of Dielectrics as Insulators*

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THE dielectric, and particularly the solid dielectric was intimately associated with the earliest experiments in electricity. As a result, it received more or less continuous study by the physicist for a long period of time which extended to about 1900. The discovery of x-rays and the electron, however, opened new and more interesting fields for study and the physicist then forgot the dielectric for the time. In a way this was somewhat unfortunate since it was at the time of the beginning of the electrical industry and dielectrics were being applied more and more as insulators and the need for a better understanding of the dielectric is quite evident. For thirty years or more the insulator was thus left in the hands of the electrical engineer who has spent a very large amount of effort in experiments and tests to make dielectrics meet his insulation needs.

The physicist has recently become interested in dielectric research again in a preliminary way and a small group in industrial research for the past few years have been using physical methods in the study and application of dielectrics as insulators. It is the purpose of this discussion to describe some experiments which have arisen in the study of insulation and which it may be possible to explain in terms of quite well-known physical phenomena; namely, dipole rotations, gaseous ionization, and ionic and electronic currents. To many, this will no doubt be a new way of thinking of the dielectric, but the internal mechanism of such a material under electric stress can only be due to the action of the three electrical entities mentioned. It is also the intention of the author to emphasize a rather new concept of dielectric breakdown; that the apparent dielectric strength of materials may be due as much to mechanisms at the metal-insulator boundary as to the dielectric material itself.

Dielectrics include all types of material, namely; solids, liquids and gases, but in general, gases are not of so much interest as an insulator. Gases are of most interest from the standpoint of the ionization and de-ionization processes, or in other words, from the point of view that they can be readily made conductors and nonconductors. Their insulating value in general is small. It is possible that some of the information gained from the study of gases can be used in a study of liquid or solid insulators, but even that is apparently a considerable step. Ionization potentials, ionization by collision, critical potentials, etc., do not seem to apply to liquids or solids in the same sense, probably due to the fact that intermolecular distance, intermolecular force, mobilities, mean free paths, freedom of rotation, etc., are of a different order of magnitude.

Concerning liquid and solid dielectrics which I wish to discuss, we really know very little of the internal mechanism. The properties to be explained were practically all known by the end of Faraday's work, but the mechanism which produces them are to a large extent even yet a matter of theory. It will be well at this stage to point out just what are these properties in which we are interested and they are therefore enumerated with some discussion.

1. All dielectrics so far as we know are conductors to some degree. By superpurification of some oils, the resistivity has been increased to the order of about 10^{18} ohm-cm which indicates impurities as a major cause of dielectric conduction, but even this may not explain all cases.

The temperature coefficient of conductivity for

* Presented at the Second Conference on Industrial Physics held by the physics department, University of Pittsburgh, May 22, 1937.

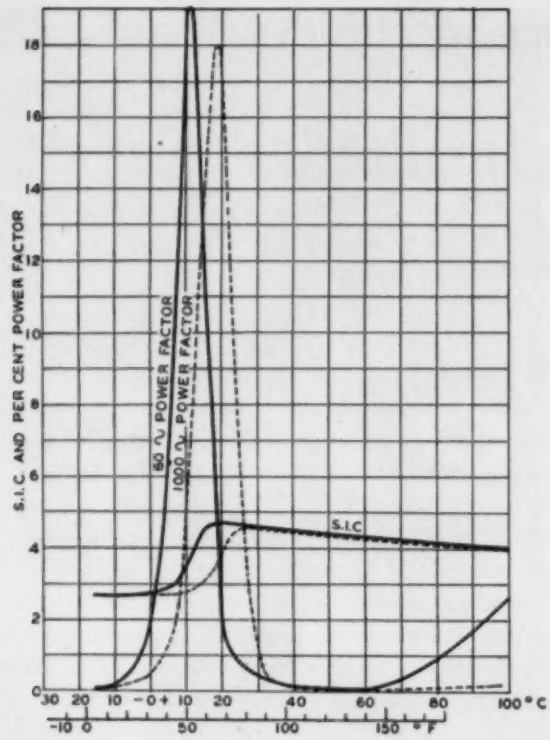

FIG. 1.

dielectrics is positive, negative for metals, which would indicate free electrons do not play a role. The dielectric constant is also small and finite which indicates bound electrons. The small normal conductivity is therefore usually considered as electrolytic. I shall later point out a critical condition in which electrons may play a role leading to a high abnormal conduction and even dielectric failure.

Superimposed on conduction is a phenomenon called dielectric absorption or the decrease of conductivity with time of voltage application, this decrease being as much in some cases as 10,000 times in a few seconds. A considerable part of the absorption is reversible, capable of flowing out of the dielectric solid upon short circuit.

Dielectric loss under a.c. potentials, due evidently to the same mechanism as absorption, is also very important to insulation application, but its explanation depends upon the same factors as absorption and conduction.

A fourth property of importance is that of dielectric constant or specific inductive capacity. In the study of dielectrics, we divide this property into two types, usually called the true and apparent S.I.C. The true S.I.C. should obey the law $N^2=\mu$, and should be the value measured at infinite frequency. The apparent S.I.C. is the S.I.C. due to displacement of the electron orbits of the atoms, plus the polar and ionic displacements which are involved in dielectric absorption and dielectric loss.

Finally, we have dielectric strength or dielectric failure where the insulator breaks down. The mechanisms are those which are associated with some critical conditions to be discussed later, but are far less constant and more elusive than similar phenomena for gases.

Before entering a discussion of actual experiments on dielectrics, I should like to describe briefly the methods of attack of the problem and particularly to point out differences between the methods of the past and those of the present and future. The methods we use depend upon the tools available and it is to be expected that the methods of research on dielectrics will depend upon the parallel developments of physics in

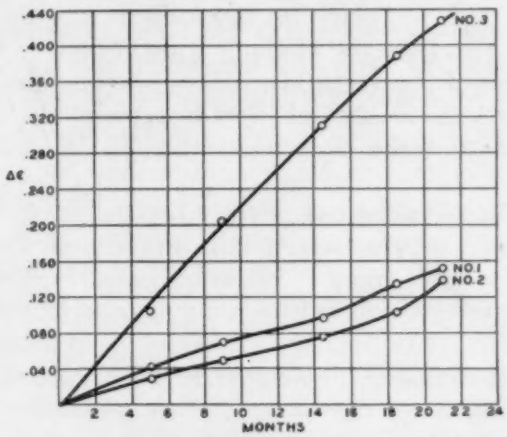

FIG. 2. Change of dielectric constant of oils in use in transformers.

general so that those remarks on methods are merely to remind you of what is going on in physics that affects this particular problem. Practically all of the earlier work and even considerable at the present time is characterized by a study of large masses of material as a whole with the mechanism of dielectric absorption the chief problem. Most of the work is based also on Maxwell's idea of the dielectric in which he tried to explain the imperfect dielectric as he called

it, in terms of resistance and dielectric constant, in other words, in terms of circuit constants R and C. Maxwell considered the dielectric to have a true and characteristic conductivity, a concept now largely abandoned. To Maxwell's theory has been added the idea of ions moving against frictional forces and thus the idea of a time relaxation factor for such ions. Experimentally, it has been difficult to test such theories, but in recent years some experiments have at least given evidence that these theories are in agreement with the overall behavior of the insulator. At the present time, it is quite evident that an understanding of the internal mechanism of the dielectric depends upon an understanding of the problem of the solid state as a whole, in other words, it is merely a phase of that problem which also includes metallic conduction, ferromagnetism, elastic properties, optical properties and thermal properties of solids.

I shall now describe two or three types of experiments which are very important to the insulation engineer and in which there are quite evident problems for the physicist.

Dipoles in Insulators

That dipole molecules with permanent electric moments should be of practical importance in liquids is to be anticipated, but a few examples will be of interest. One of the most important involves liquids where such polar molecules give an effective dielectric constant which is about twice that of the usual value for nonpolar dielectric liquids, making these polar liquids applicable to capacitors. Such liquids are characterized, however, by electrical dispersion, that is wide variations in electrical properties as a function of frequency and also wide variations in electrical properties as a function of temperature. Fig. 1 shows the variations of 60-cycle power factor and dielectric constant with temperature. The very high peak in power factor value and the drop in dielectric constant is due to the fact that the material is approaching solidification and becoming very viscous. Such capacitors may give trouble in resonance circuits when ambient temperatures are too low. Similar results are found on heavy cable oils where rosin (abetic acid) is mixed with the oil although the effect is not so marked. If the a.c. voltage gradient is sufficient on capacitors with liquids represented in Fig. 1, the dielectric losses keep the capacitor warm, or in other words, above the power factor resonance. The oxidation of insulating oils forms polar acids. The change in dielectric constant of the oil can thus be used as a measure of the degree of oxidation (Fig. 2). It also gives a method of evaluating or comparing oils on accelerated oxidation tests. That dipole structures also play a role in solid insulations is becoming evident although it is not definite if the moments are permanent or induced. Cellulose is an example, the electrical dispersion curves being shown in Fig. 3. We would not expect the long cellulose molecule to rotate except about its lengthwise axis and since from the molecular structure we should expect electric moments perpendicular to the molecular axis, this may offer an explanation, although the presence of a few of the highly polar water molecules may be sufficient. A similar effect has been observed for rubber in spite of the peculiar shape we attach to the rubber molecule. Scott, McPherson and Curtis[1] at the National Bureau of Standards has reported on the dispersion characteristics which apparently can only be explained by the presence of dipole structures. Unpublished results by Dr. G. L. Clark and Dr. W. J. Warren of the University of Illinois upon the x-ray properties of rubber before and after a time application of

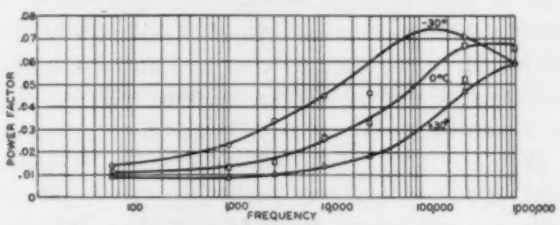

FIG. 3 a. Power factor *vs.* frequency for G.F. dried Cellophane.

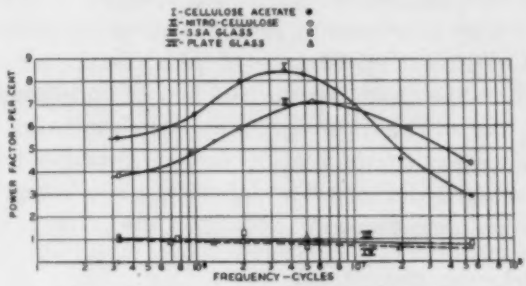

FIG. 3 b. Power factor *vs.* frequency.

voltage to the samples, show that less stretching is required after the voltage treatment to produce a given fiber pattern than before voltage treatment. This would indicate an orientation of the long rubber molecule perpendicular to the field, or in other words, again suggests an electric moment perpendicular to the molecular axis. I am indebted to Dr. Clark and Dr. Warren for permission to quote from their results.

These experiments just described emphasize the practical importance of polar structures as well as the fundamental problem of understanding their behavior. Fig. 3b suggests for example, the possibility of sealing safety glass by heat developed directly by high frequency losses in the cellulose material.

Dielectric Breakdown

To the engineer, dielectric breakdown is the most important of all properties, but of the mechanism leading to failure, less is known than of the other characteristics. I shall now describe several experiments from which I hope to draw some conclusion concerning this breakdown mechanism, and I am sure the experiments themselves will be of considerable interest. Let us consider first the breakdown of insulating oil. The curves of Fig. 4 represent typical data on breakdown of an insulating oil as a function of temperature. A peak value is shown at about 70° C. Clark has published data showing the peak at about 100° C. It is rather unexpected to obtain the better strengths at the higher temperatures. There is as yet no definite explanation for this result, but Clark[2] has made an extensive

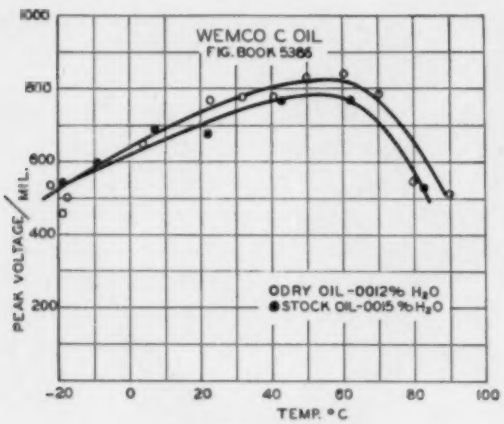

FIG. 4.

study with at least some very interesting correlations. Fig. 5 from Clark shows that the amount of gas absorbed by the oil as a function of temperature gives a curve similar in shape to the breakdown curve. The more gas absorbed in the oil, the greater the dielectric strength. This is also made more evident by a second curve (Fig. 6) from Clark in which the oil was first very completely out gassed and then breakdown tests made as a function of time of exposure to air. The resemblance of this curve to the breakdown of a gas as a function of pressure, the minimum strength occurring at about a cm Hg pressure and then rising as the vacuum improves on the one side and as the pressure increases on

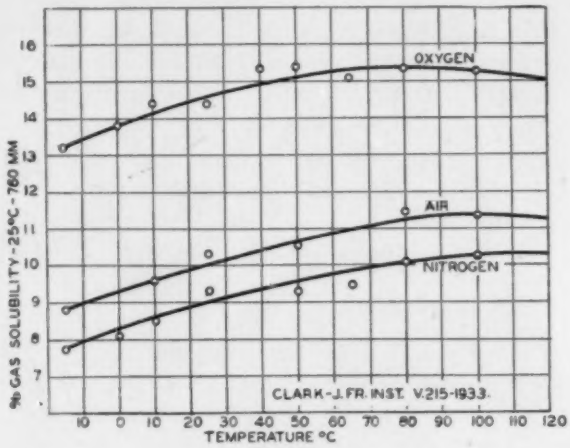

FIG. 5.

the other. The explanation for gases is well known, but is still unsolved for oil. Clark has offered several suggestions and has especially emphasized ionization by collision as a factor near the breakdown potential. A difficulty arises in that mean free paths to permit such ionization are hardly conceivable. We are dealing with spacings a thousand times smaller in liquid than gases. He suggests high speed ions or clusters may create voids behind them into which the absorbed gas diffuses. There is also the increase in dielectric strength with increased pressure on the oil which might lend strength of the argument for ionization by collision, but other phenomena may also be affected by pressure.

Walther and Tscheljustkina[3] have recently checked the behavior of gas in less viscous media as toluol and found no effect upon the dielectric strength from absorbed gases, but a decided

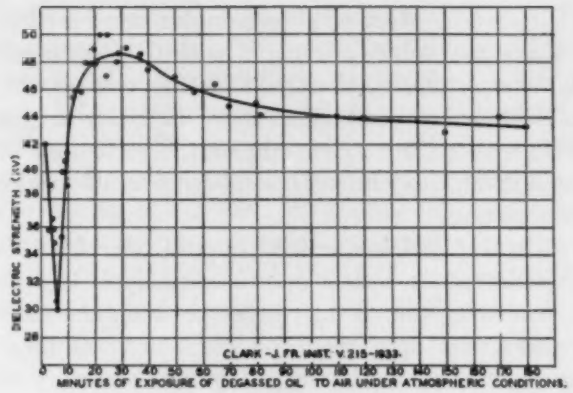
DIELECTRIC STRENGTH (KV)
CLARK - J. FR. INST. V. 215-1933.
MINUTES OF EXPOSURE OF DEGASSED OIL TO AIR UNDER ATMOSPHERIC CONDITIONS.

FIG. 6.

lowering for emulsified gas. This result is not as surprising as the very marked opposite effect found by Clark for oil. It is my own opinion that gas should affect the strength of oil to some extent, but that it is necessary to understand the mechanisms at the electrode surfaces to understand how dielectric punctures take place and I shall now proceed to experiments in solids, a study of which I believe will give us a partial clue as to what that mechanism at the electrode may be.

The Behavior of Electrons in Dielectrics

It is generally assumed as stated before that conduction in dielectrics is electrolytic. There are but few if any free electrons in true insulators, that being assumed as a fundamental difference between the conductor and the nonconductor. It is possible and probable that at the instant of dielectric failure and even just prior to failure that conducting electrons exist, however. Some experiments will now be described in which electrons play an important part in dielectric behavior.

A first simple experiment which many may be interested in trying consists in a circuit shown in Fig. 7. To the filament of a lighted incandescent lamp connect the negative of a battery, 200–400 volts, through a sensitive ammeter to a metal or conducting cap on the glass bulb of the lamp. The cap of 2 to 4 sq. inches area may be made of lead foil or aquadag or other means of making rather intimate contact with the glass. Currents from a few microamperes to milliamperes will be observed depending upon the temperature or the glass bulb. So far as I know, no one has ever separated the electrolytic and electron currents in this experiment but it is quite probable that a good fraction is due to electrons. A similar experiment is performed by Pohl[4] using a rocksalt crystal as shown in Fig. 8 where he attaches two point electrodes to the faces of the crystal, the crystal being of the order of 1 cm cube. The crystal temperature is raised to about 550°C and d.c. voltage applied. As the voltage is increased, a colored and rather opaque cloud forms in the crystal around the negative point and gradually swells into the whole crystal until it reaches the anode. Or as Pohl originally reported the experiment, the voltage can be removed when a small spherical cloud has been formed, the point electrodes replaced by plate electrodes and the cloud moved bodily back and forth through the crystal. If the cloud is allowed to reach the point anode, an avalanche of metal ions from that electrode begin to move through the crystal. By reversing the potential when the point electrode is used, the cloud can be readily drawn or conducted out. Pohl has shown that this electron cloud shows selective absorption of light which indicates that the electrons are closely associated with the ions of the crystal. Also he has calculated if the electrons were free, such densities of electrons would exert explosive forces on the crystal and therefore they must be rather well bound. They move apparently by jumping from one ion to another or to better express ourselves, they move through outer low energy levels for the

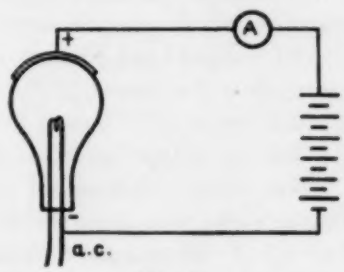

FIG. 7.

electrons of the ion, that is, levels near but outside the normal valence levels. If a sufficient current of these electrons is used, the crystal fails electrically.

The start of electrons into the crystal from the metal electrode is evidently a function of

potential gradient at the boundary. This experiment also suggests an explanation of the experiment with the lamp bulb in that the electrons from the hot filament no doubt strike and diffuse

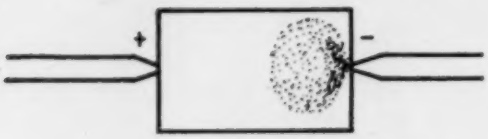

FIG. 8.

through the glass until they strike the anode layer. Ions from the anode then tend to move into the glass, the sodium moving ahead. The correlation is not complete, since in the sodium chloride crystal in Pohl's experiment the copper ions from the anode move rapidly into and through the crystal with but little motion of sodium. It is also of interst to point out that in all experiments on the conductivity of dielectrics it is the positive ion only which moves, which suggests that electrons carry any current in the opposite direction.

In experiments similar to that of Pohl and possibly the experiment with the lamp bulb, there is a sort of lag or reluctance on the part of the current to start, but once started at a somewhat elevated voltage, the experiment can be carried out at any future time at lower voltages. As a matter of fact, if the voltage is not immediately reduced when the electron cloud starts, the crystal punctures. This may be suggestive of the behavior of dielectrics at breakdown and particularly for thermoelectric failures.

The physicist responsible for insulation studies soon recognizes that the dielectric strength of his material is much lower than should be expected. As a result, he has fallen back on the defect theory of solids as an explanation of the discrepancy in the same way that the discrepancy between theoretical and measured elastic properties are explained. There are, however, other possible physical explanations for some rather puzzling experiments on dielectrics and I should like to make one or two suggestions.

It is well known that the apparent dielectric strength of an insulator varies with the medium in which the sample is immersed during test. Data are shown in Fig. 9 from Inge[5] and Walther's work. Mica or glass samples punctured in oil and the values compared with data obtained for samples tested in oil to which several percent of acetone has been added show the latter to give values about three times the first. The acetone or aniline impurity makes the oil considerably more conducting.

The explanation which I would offer for this experiment is based upon an analysis of the behavior of the contact layer between the electrode and sample. With the less ionized oil, there is a tendency for the thin layer to puncture at some spot allowing an avalanche of electrons from the metal to cross the gap striking the sample surface. The heating and bombarding effect carries the electron into the material and once started, the reaction continues to complete failure. When the aniline is used, sufficient electrolytic ions are present to keep the dielectric surface at the electrode potential thus reducing the danger of a concentrated arc bringing an avalanche of electrons until much higher voltages are reached where some triggering device again starts the electron avalanche from the metal. On the basis of the above theory, the problem

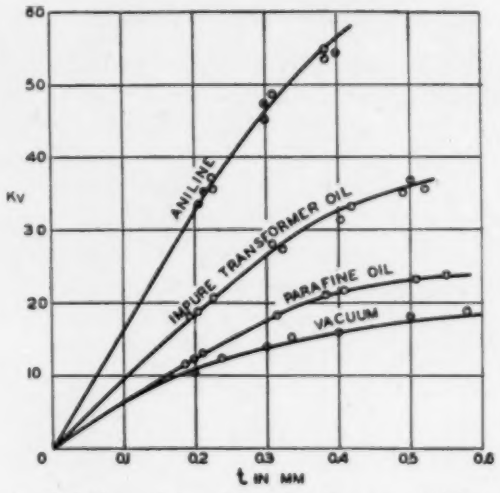

FIG. 9. Relation of breakdown voltage to thickness of glass under various conditions.

of dielectric strength is not so much a problem of the dielectric itself as the prevention of the formation of a concentrated arc from the electrode. Just what condition or mechanisms can cause the electron flow from the metals is a matter for study, but it is reasonable to expect that the boundary gradients at the junction

between a conductor and a dielectric play a considerable role in the apparent behavior of the insulator. Oxide rectifiers are merely a limiting case of such boundary phenomena. Boundary effects may be even more critical for liquids than solids. A simple experiment demonstrating the action of the electron avalanche consists in puncturing a liquid insulator from a point to sphere under the liquid, Fig. 10 A. By withdrawing the point as shown in Fig. 10 B, the breakdown point to sphere may be less than for case A.

Von Hippel[6] has also reported an experiment wherein sodium chloride crystals are punctured at room temperature. Cracks along the various planes of the crystal move out from the negative electrode and not the positive showing again that electrons are involved.

Another phenomenon which could evidently be explained on the basis that the boundary effects are the dominating factors, is that of the very large increase in apparent dielectric strength with decreasing thickness, particularly for rather small thicknesses. There are numerous other experiments, as for example the very decided decrease in apparent strength of relatively thin materials with increase in area tested, which may be explained by such a theory.

In conclusion, I should like to point out that the explanation of most all of the experiments described are as yet not proven, but I have attempted to show by the discussion some of the problems the industrial physicist meets in dielectric research and to show how they may fit in with our present knowledge of physical behaviors. We know now, of course, that the problem of the solid dielectric is merely a part of the general problem of the solid state of which metallic conduction, magnetism, etc., are also a part and for which physics has just become equipped to deal. The experiments described along with many others merely constitute a group of phenomena to be studied using the modern tools of physics.

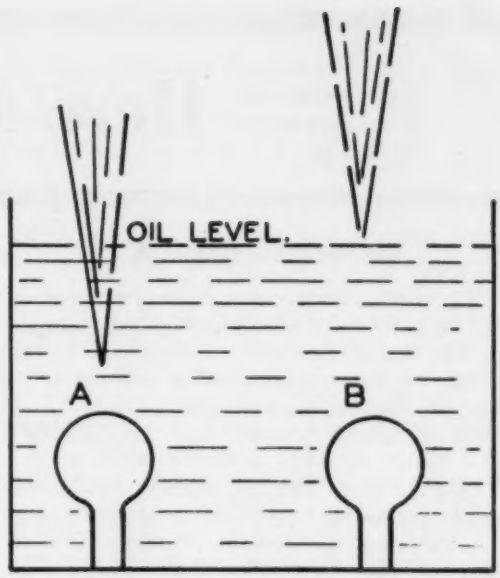

FIG. 10. Experiment showing action of an electron avalanche in puncturing a liquid insulator.

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4. Pohl, Physik. Zeits. 107, Feb. (1934).
5. Archiv. f. Elek. **24**, 209 (1930).
6. Zeits. f. Physik **68** (1931).

Here and There

Editorial Office of the J. A. P.

Dr. Elmer Hutchisson, editor of the *Journal of Applied Physics* has returned to the University of Pittsburgh after a year's leave of absence spent at the American Institute of Physics. He has been promoted to professor and acting head of the department of physics at Pittsburgh. Manuscripts and editorial correspondence for the *Journal of Applied Physics* should be addressed to him at the University of Pittsburgh. Proof and correspondence concerning articles in the process of publication should be addressed to the Publications Manager, American Institute of Physics, 175 Fifth Avenue, New York City.

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Symposium on Biophysics Planned

A special conference meeting of research men interested in biophysics is planned for November 4, 5 and 6 in Philadelphia. Invited papers will be presented by leaders in such fields as electro-biology, radio-biology, energetics of living systems, etc. The meeting will be held under the auspices of the American Institute of Physics with the cooperation of the Johnson Foundation of the University of Pennsylvania. Anyone interested in research or teaching in the field of the conference may obtain an invitation by sending his name and address to the office of the Institute. A more complete announcement will be made later.

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The Charles E. Mendenhall Fellowship Fund

Professor C. E. Mendenhall died in August, 1935, after about thirty-five years on the staff of the physics department of the University of Wisconsin. His friends and associates desired to set up some kind of memorial to him in the university. A purely personal thing like a portrait is not in harmony with his manner of life which was spent largely in helping everyone about him. He had been greatly interested years ago in obtaining financial help for some graduate students to enable them to pursue their experimental work over the summer, and he succeeded in obtaining such help for a number of years. It thus appeared to his friends that even a very modest sum of money devoted to such help would be compatible with his character and would appeal to his judgment.

The following committee was chosen to carry out this plan: Farrington Daniels, Louis M. Hanks (Treasurer), Mark Ingraham, Theodore Lyman, Robert A. Millikan, John R. Roebuck (Secretary), Joel Stebbins, and R. W. Wood.

A circular letter was sent to all those from whom there was some reason to expect help. A sum of $2100 has now been accepted by the university as a trust fund, with the provision that it may be added to freely and that the income shall be used for assisting graduate students in experimental physics as recommended by the physics department of the university. It is felt that the large number of contributors makes this a real memorial to Professor Mendenhall.

★

Denver Meeting of the American Physical Society

(Report from Paul Kirkpatrick and Henry A. Barton)

The Society held on this occasion its regular summer Pacific Coast meeting. A good attendance at all sessions was observed, including members and guests from the east as well as from the Pacific Coast and the region of Colorado. The first (Friday morning) session was a Symposium on Astrophysical Problems of the Ionosphere. This session was arranged and held jointly with Section D—Astronomy and the Astronomical Society of the Pacific. The presiding officer was Professor Philip Fox, Adler Planetarium, vice president of Section D. This interesting symposium of invited papers dealt with "Fundamental Mechanisms in the Ionosphere" by N. E. Bradbury, Stanford University; "Terrestrial Magnetic Variations and the Ionosphere" by A. G. McNish, Carnegie Institution of Washington; "Sudden Disturbances of the Ionosphere" by J. H. Dellinger, National Bureau of Standards and "Bright Chromospheric Eruptions" by R. S. Richardson, Mount Wilson Observatory of the Carnegie Institution of Washington. The symposium brought out the considerable degree of association between phenomena in the upper atmosphere of the earth and the spectacular eruptions and activity on and above the surface of the sun. Relations between variations of earth magnetism and electric currents in the ionosphere were discussed, and the bearing of laboratory observations upon ionospheric phenomena was presented. The papers from this symposium will be published in an early issue of the *Journal of Applied Physics*.

On Friday afternoon, several short papers were presented on the subject of cosmic rays, their effects in the laboratory and at high altitudes and as a function of time and atmospheric conditions. Other papers dealt with topics in the fields of thermodynamics, x-rays, apparatus for research on the atomic nucleus, ultrasonics and the photographic study of lightning. Professor R. E. Nyswander of the University of Denver presided.

The Saturday morning session was held jointly with Section B of the American Association for the Advancement of Science. The program took the form of a sym-

posium of invited papers on Cosmic Rays and High Altitude Effects. Professor Stearns made some introductory remarks describing the Mt. Evans high altitude laboratory and pointing out its usefulness as a research station in various scientific fields. He then introduced Dr. Thomas H. Johnson who described "Further Experiments with the Geomagnetic Cosmic-Ray Effects and Their Bearing upon the Nature and Energy Distribution of the Primary Cosmic Radiation." The paper dealt largely with observations made by the author but also reviewed the present degree of understanding of the various observed phenomena and their dependence upon latitude, time and the presence of magnetic storms.

The second paper as scheduled on the program was on a kindred subject, namely, "The Nature of the Penetrating Cosmic-Ray Particles," which was presented by Professor J. C. Street of Harvard University. This paper was based on the original work of the author using various forms of counters and cloud-chambers. As a result it appears that the penetrating particles are something new—probably possessing the same charge as an electron but greater mass. The particles are considerably lighter than protons.

The third paper of the program departed from the field of the other two, being devoted to "The Importance of Observations from the Upper Atmosphere in Long Range Weather Forecasting." This paper was presented by Professor Hurd C. Willett of the Massachusetts Institute of Technology. Professor Willett discussed the methods and results of systematic high altitude observations and pointed out that only when it is understood how the observed conditions are set up and maintained can progress be made in long range weather forecasting.

On Saturday afternoon a number of short papers were read on a variety of subjects. Several dealt with ionization in gases at various pressures and temperatures. The ionization along cosmic-ray tracks was discussed. Other papers described experimental studies of electrode surface and other phenomena in gaseous discharges. One paper described a sensitive method for the measurement of the age of rock samples by observing their radioactivity and helium content. There were additional papers on spectroscopy and optical effects. A new design of air-driven ultracentrifuge was described and its biological applications indicated. Professor W. B. Pietenpol of the University of Colorado presided.

★

Members of the Canadian National Research Council elected for three-year terms are Sir Frederick Banting, head of the Banting Institute of the University of Toronto, and Professor E. F. Burton, head of the department of physics; W. R. Campbell, Windsor, general manager of the Ford Motor Company of Canada; Professor R. H. Clark, head of the department of chemistry, University of British Columbia, and Professor E. P. Fetherstonhaugh, dean of the faculty of engineering and architecture, University of Manitoba.

Officers of the National Research Council, 1937–1938

The National Research Council announces the reappointment of Dr. Ludvig Hektoen, director of the John McCormick Institute for Infectious Diseases in Chicago, as chairman of the council for the year beginning on July 1, 1937.

The officers of the divisions of science and technology of the council for the coming year, among whom are several replacements, are as follows:

Physical Sciences
LUTHER P. EISENHART, chairman; professor of mathematics and dean of the Graduate School, Princeton University.
H. A. BARTON, vice chairman, director of the American Institute of Physics, New York City.
Engineering and Industrial Research
VANNEVAR BUSH, chairman; vice president and dean of the School of Engineering, Massachusetts Institute of Technology.
HOWARD POILLON, vice chairman; president of the Research Corporation, New York City.
Chemistry and Chemical Technology
HERBERT R. MOODY, chairman; professor of chemistry and director of the chemical laboratories, College of the City of New York.
Geology and Geography
CHESTER R. LONGWELL, chairman; Henry Barnard Davis professor of geology, Yale University.
ROBERT S. PLATT, vice chairman; associate professor of geography, University of Chicago.
Medical Sciences
ESMOND R. LONG, chairman; professor of pathology, School of Medicine, and director, Henry Phipps Institute, University of Pennsylvania.
HOWARD T. KARSNER, vice chairman; professor of pathology and director of the Institute of Pathology, Western Reserve University.
Biology and Agriculture
R. E. COKER, chairman; professor of zoology and chairman of the Division of Natural Sciences, University of North Carolina.
E. C. STAKMAN, vice chairman; professor of plant pathology, University of Minnesota.
Anthropology and Psychology
W. S. HUNTER, chairman; professor of psychology, Brown University.
CARL E. GUTHE, vice chairman; Director of Museums, University of Michigan.

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At the Museum of Science and Industry, Chicago, Dr. F. C. Brown, director of the Annual Science Exhibit of the American Association for the Advancement of Science, formerly director of the Museum of Science and Industry, New York, has been appointed curator of physics, and Dr. C. R. Moulton, of Northwestern University, curator of chemistry.

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The Rev. Dr. James B. Macelwane, S.J., has been appointed director of an Institute for Geophysics which has been established at St. Louis University. It is planned that the institute become a clearing house for geophysical records and related studies of earth structure in the central states. Its inauguration was made possible by gifts to Father Macelwane from prominent St. Louisans.

Science, August 6, 1937

★

A ceremony was held at the Franklin Institute on July 22 in memory of the late Frederic Eugene Ives, who died on May 27. His son, Dr. Herbert E. Ives, presented to the institute the original patent and other material from the Ives laboratory.

Science, July 30, 1937

Comstock Prize

The Comstock prize of the National Academy of Sciences will be presented to Dr. Ernest O. Lawrence, professor of physics at the University of California, at the meeting of the academy to be held in Rochester from October 25 to 28.

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Dr. Carl F. Eyring, professor of physics and dean of the College of Arts and Sciences at Brigham Young University, has been appointed president of the recently created New England Mission of the Latter Day Saints Church. Dr. Eyring will have headquarters in Boston.

Science, August 13, 1937

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Professor E. U. Condon of Princeton University spent six weeks during July and August working in the research laboratory of the New Jersey Zinc Company at Palmerton, Pennsylvania.

For the coming year Dr. Condon will be at the Research Laboratories of the Westinghouse Electric and Manufacturing Company at Pittsburgh, Pennsylvania.

Dr. Irving A. Cowperthwaite who has been a research associate in the teaching of physical science in Teachers College has been made head of the Research and Development Department of the Thompson Wire Company, 41 Mildred Avenue, Mattapan, Massachusetts.

★

Movie of Marie Curie's Life

A screen version of the life of Marie Curie, co-discoverer of radium, which is being adapted from Eve Curie's story of her mother, now running in The Saturday Evening Post, will be produced by Universal Pictures next season. There is considerable interest as to who will be cast in the role of Madame Curie. No one has been definitely set as yet. Among those who have been mentioned are Irene Dunne and Norma Shearer. When Miss Dunne was in Paris last year, she was so much interested in Madame Curie that she called on her daughters, Eve Curie and Irene Curie-Joliot, winner of the Nobel Prize for Chemistry in 1935. Miss Dunne has a natural aptitude for portraying a character whose life extends from girlhood to old age in one picture.

Some of the New Books

Sound. ARTHUR TABER JONES, Pp. 450+xii, Figs. 141. D. Van Nostrand Company, New York, 1937. Price $3.75.

The advances in acoustics have been so rapid in recent years that the older books on the subject give an inadequate picture of the present state of the science. In this book are included many of these more recent developments. We therefore find, in addition to the subjects usually discussed in elementary books on sound, sections on the production of noises, noise reduction, sound ranging, prospecting for oil, reproduction of speech and music and architectural acoustics.

While the subject matter is treated in an elementary manner, copious references to original sources are given in footnotes so that the more serious student may readily find a detailed treatment of subjects in which he may be particularly interested. These footnotes also give the reader a good picture of the historical development of the subject. A feature of the book is the interspersion of numerous pertinent questions which stimulate clear thinking on the part of the student and which permit him to gauge his comprehension of the matter under discussion.

The book should be of interest to any one who desires a brief nontechnical treatment of the subject. It is not necessary to have had a mathematical training in order to read the book. Those who have had an elementary course in physics will find in it discussions of many branches of sound which are scarcely touched upon in their general physics textbook. The student who has had little training in physics should obtain from this book a satisfactory introduction to the subject of sound.

C. N. HICKMAN
Bell Telephone Laboratories

The Newer Alchemy. LORD RUTHERFORD. Pp. 67. University Press, Cambridge and Macmillan Company, New York. Price $1.50.

This book contains in somewhat expanded form the material of the Sidgwich lecture of 1936. After a brief survey of radioactivity it tells the story clearly of artificial transmutation of the elements, methods and results. It is all simply said and is of absorbing interest. There are thirteen plates and a number of effective diagrams. The book is to be recommended for the lay reader or as excellent collateral reading in the elementary physics course.

JOHN A. ELDRIDGE
State University of Iowa

Sound Waves, Their Shape and Speed. DAYTON CLARENCE MILLER. Pp. 164+xi. Figs. 64. Plates 6. The Macmillan Company, New York, 1937. Price $2.75.

In this book Professor Miller has given an interesting nontechnical account of the operation of the phonodeik, spark photography of sound waves, and measurements on waves from large guns.

After a preliminary discussion of early methods of recording wave forms the mechanical and optical principles and the construction of the phonodeik are given in detail. The operation of the phonodeik and corrections for resonance effects are clearly described and a number of records showing different types of sound waves are given. For the analysis of sound waves the reader is referred to Professor Miller's book, *The Science of Musical Sounds*.

The apparatus for photographing the sound waves surrounding a bullet in flight is clearly described and several interesting photographs are shown.

Part two of the book deals with experiments on the sound waves from large guns. There are described measurements of the pressure in the sound impulse at different distances and different directions from the gun by means of a special type of gauge called a "baroscope." The results are shown in the form of curves. The use of the phonodeik for determining the wave form of the sounds from large guns is described and several of the resulting records are shown.

One chapter deals with measurements on the velocity of propagation of sound at different pressures in the sound impulse. For these measurements use was made of six microphones and a string galvanometer containing six strings. All six deflections were recorded on a single film. The experiments showed that the velocity of a sound pulse varied with the distance from the gun in such a way that the effective center of the sound wave was shot out of the gun and came to rest several hundred feet in front of the gun. Equations are given describing this type of wave motion with the velocity of the wave center decreasing according to an exponential law. The experimental results observed for several directions of propagation were found to fit the equation.

In the last chapter measurements of the velocity of sound over ranges to 20,312 feet were described and the final result compared with that obtained by other methods. The value of 331.36±.08 meters per second was determined for the velocity of sound in free air at 0°C.

The book as a whole is very interestingly written, it is well illustrated, and clearly presents data in usable form. It should prove of value primarily to those interested in the military aspects of measurements on sound.

J. G. WINANS
University of Wisconsin

Origins of Clerk Maxwell's Electric Ideas as described in familiar letters to William Thomson. Edited by Sir Joseph Larmor. Pp. 56. Cambridge University Press and Macmillan Company, New York, 1937. Price $1.00.

The letters in this little book were originally issued as Part V of Volume 32 of the *Proceedings of the Cambridge Philosophical Society*. Now they are made available to a wider circle of readers, who will be interested in gaining an insight into the mentality of a man of such ability. Most of the letters were written during the days of his earlier development, beginning in 1854. In many cases he is seeking advice from Thomson, who was several years his senior.

The book does not give a connected development of any one subject. Rather one is impressed with the diversity of Maxwell's interests. He writes on the laws of color vision, currents induced in a rotating sphere, hydrodynamics, general theory of optical instruments, a model or analogy for the electrodynamic field (for which he derived the velocity of waves to be equal to the velocity of light), theory of dielectric displacement, stress in a gas between hot bodies, and many other topics even including peacocks as gardeners. These letters, though informal, are clear and concise, and give evidence of straight thinking. He is careful in stating his assumptions, and is continually seeking methods to test his theoretical results. Some of his letters refer to his teaching problems, and describe ingenious devices used for demonstrations.

W. H. MICHENER
Carnegie Institute of Technology

Fundamentals of Engineering Electronics. WILLIAM G. DOW. Pp. 604+xiv, Figs. 200. John Wiley & Sons, New York, 1937.

Professor Dow, with the aid of his associates at the University of Michigan, has written a text for students of electronics based on eight years of teaching experience. The main emphasis is placed upon the necessary physical concepts for both the design and use of electronic devices. Although the book does not contain lengthy mathematical derivations, the type of mathematical representation is concise and is generally indexed in a novel manner to indicate the type of units involved in each formulation. The most unusual feature of Part II of this book is the amount of material on modern spectroscopy which it contains. By its inclusion, in two chapters, an interesting glimpse into this field is afforded the student of practical engineering. The subject material used for many of the problems included at the end of each chapter has been selected from concepts and results of investigations that have, in the main, been the concern of many physics laboratories.

In addition to chapters on cathode rays and photosensitive devices, the last four chapters are devoted to the fundamentals and utilization of gaseous discharge devices. Two features which add to the value of the book are the excellent group of tables and the quite complete bibliography at the end.

This book has been carefully planned and well executed for use as a text for a full year's course in electronics. It is thoroughly up to date and should find favor as a reference book for workers in the electronic field as well as for a textbook.

H. E. MENDENHALL
Bell Telephone Laboratories

Among our Contributors

Merton W. Jones was born in Groton, New York. He received his A.B. degree from Cornell University and his M.S. in physical chemistry from the University of Wisconsin. He has been undergraduate assistant at Cornell University, Science Master in a private school, assistant physicist with Taylor Instrument Companies and is now an instructor in physics at the University of Colorado.

Dr. George L. Clark received the A.B. and D.Sc. degrees from DePauw University in 1914 and 1937, respectively, and the M.S. and Ph.D. degrees from the University of Chicago in 1914 and 1918, respectively. After wartime work in the Chemical Warfare Service, he was Associate Professor of Chemistry at Vanderbilt University, 1919–1921; National Research Fellow, Harvard University, 1921–1924; Assistant Professor of Applied Chemical Research, Massachusetts Institute of Technology, 1924–1927; Professor of Chemistry, University of Illinois, 1927 to date. He is the author of *Applied X-Rays in the International Series in Physics*, published by McGraw-Hill.

Dr. Julian M. Blair was born at Watertown, Tennessee, in 1892. He received his B.S. from Vanderbilt in 1914; his A.M. and Ph.D. from Stanford in 1920 and 1932, respectively. He was professor of chemistry and physics at Rollins College from 1917 to 1921. Since 1921 he has been assistant professor of physics at Colorado.

Dr. James A. Chiles, Jr., was born in Champaign, Illinois, in 1909. He received his A.B. degree at Wofford College in 1931 and his M.A. and Ph.D. degrees in physics at the University of Virginia in 1933 and 1936. During the years 1931 to 1933 he held a Service Fellowship in Physics at the University of Virginia, and he is now a research associate in the Department of Anatomy at the College of Physicians and Surgeons, Columbia University, where he is conducting experiments with the ultracentrifuge.

Dr. Enno Wolthius, born in 1911, received his elementary education in Grand Rapids, Mich., his A.B. degree from Calvin College, M.S. from the University of Michigan and Ph.D. from the University of Illinois in 1937. He is now employed by the General Aniline Works in Grasselli, N. J.

Dr. Joseph Slepian has been Consulting Research Engineer at Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. since 1916. He received his A.B. in 1911; his A.M. in 1912; and his Ph.D. in 1913 from Harvard University. He was an Instructor at Cornell 1914–1915.

Dr. Ruric Coin Mason is Research Engineer at Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa. He was born at Bentonville, Arkansas, September 6, 1903. He received B.E.E. from the University of Arkansas in 1924, and his M.A. and Ph.D. from Princeton University. Since 1924 he has been at Westinghouse Electric and Manufacturing Company.

Contributed Original Research

The Experimental Validity of Paschen's Law and of a Similar Relation for the Reignition Potential of an Alternating Current Arc

J. Slepian and R. C. Mason
Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania
(Received July 15, 1937)

THE relation between the sparking potential, electrode separation and pressure, originally discovered by de le Rue and Muller,[1] and now generally known by the name of the first extensive investigator Paschen,[2] is widely accepted as the statement of a general and basic law. There exist general theoretical relations,[3] which indeed give a strong expectation that the sparking potential for plane electrodes should be a function of the product of electrode separation and pressure, just as found (approximately) by Paschen. It is known, however, that departures from Paschen's law are observed experimentally. To what extent, then, does Paschen's law rest on an experimentally established base?

Our interest in this question was aroused by a recent paper[4] in which a relation analogous to Paschen's law was reported for the reignition potential of an alternating current arc. Now theory may be found for the existence of Paschen's law, but the writers are not acquainted with any theory which would suggest the relation given by Cobine and Power; in fact, there seem to be good theoretical reasons why the arc reignition voltage should *not* follow Paschen's law. Yet the experimental points as shown in Fig. 4 of the paper by Cobine and Power seem to establish such a relation apparently as well as experiments verify Paschen's law for sparking potentials. Is the usual method for demonstrating the experimental validity of Paschen's law well suited for the purpose, since it seems to also show the validity of the theoretically unexpected relation of Cobine and Power?

[1] Phil. Trans. **171**, 109 (1880).
[2] Wied. Ann. **37**, 69 (1889).
[3] For example, Townsend, *Electricity in Gases*, p. 365.
[4] Cobine and Power, J. App. Phys. **8**, 287 (1937).

In the usual method, the observed sparking potential V, is plotted against the product pd, for various pressures p, and electrode separations d. Then, if these points do not spread over an extensive area, but lie in a narrow region close to some continuous curve, as for example in the Fig. 4 of Cobine and Power, the relation is regarded as established. However, this manner of exhibiting the results makes it difficult to see whether a certain important necessary condition is satisfied, without which no conclusion can be drawn.

It is quite clear, that for each point V, on the curve, there must be a number of experimental points nearby which refer to a wide range of p and d. If the different points V on the curve, have near them experimental points which refer to ranges of p or d which do not overlap in a sufficient degree, then no conclusion can be drawn as to the validity of Paschen's law. Yet from cursory examination of the curve and points, it is not easy to see whether the necessary degree of overlap has been obtained. The following, we believe, is a better method for revealing the experimental validity (or lack of validity), of a law of the type of Paschen's.

Suppose that the general relation between sparking potential (or arc reignition voltage) and pressure and gap length is of the form

$$V=f(p^m d^n), \tag{1}$$

which may be written as

$$p^m d^n = F(V).$$

Thus, for any particular value of V, V_1 say,

$$p^m d^n = F(V_1) = \text{constant}$$

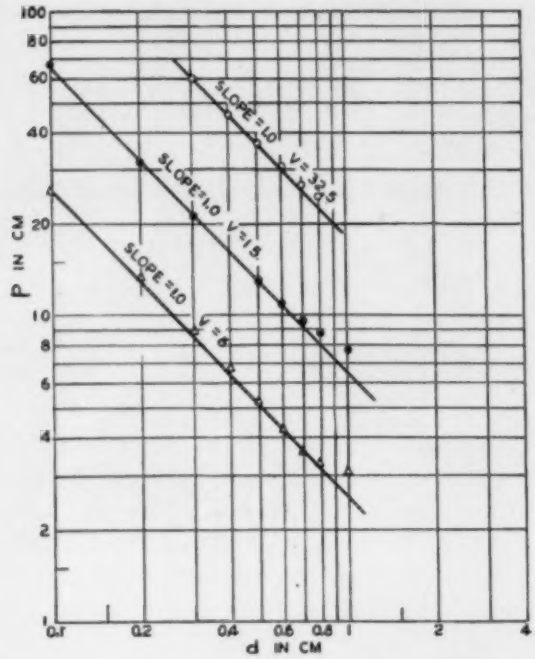

FIG. 1. Pressure *vs.* electrode separation for sparking potential of air between 1 cm spheres, data from Paschen.

and $$m \log p + n \log d = \text{constant}.$$

Thus, if relation (1) is true, a plot of $\log p$ *vs.* $\log d$, for constant $V = V_1$, should be a straight line, of slope $-n/m$. Further, for other values of $V = V_2, V_3 \cdots$, other straight lines of the same slope should be found in the region for which Eq. (1) holds. If Eq. (1) more specially represents Paschen's law, then $n = m$, and the slope of the lines of constant V should be -1. This method of exhibiting the experimental results substitutes the collinearity of points and the slope and parallelism of lines as criterions for the existence of relations of the type of Eq. (1), for the rather vague and indefinite way of judging the sufficiency of overlap of data from inspection of points on a V *vs.* pd curve.

We have examined the data of a few investigators in this field. In Fig. 1 we plot p *vs.* d on log-log paper for three values of V, for data taken from Paschen. The solid lines are drawn with slope -1, and each line passes near six or more points. The experimental points fall very well along the lines, except for large d. A departure might be expected in this case, for actually Paschen used spherical electrodes, whereas Paschen's law should be expected to apply only for plane electrodes.

In Fig. 2, we plot data from Carr[5] for sparking potentials, around the minimum point, between planes separated by an insulating ring. By inspection, what seemed to be the best straight lines were drawn. Only two of the slopes are not unity. Furthermore, the number of points through which each line passes well, are respectively, 2, 5, 5, 5, 5.

From experimental data of Fricke,[6] for H_2 in uniform fields, Fig. 3 has been plotted. The points, five or more for each curve, fall very well on straight lines. The slopes of these, however, are not constant but vary from -1.03 to -1.19. In these three figures we see that Paschen's law is definitely departed from, but the departures are not very great.

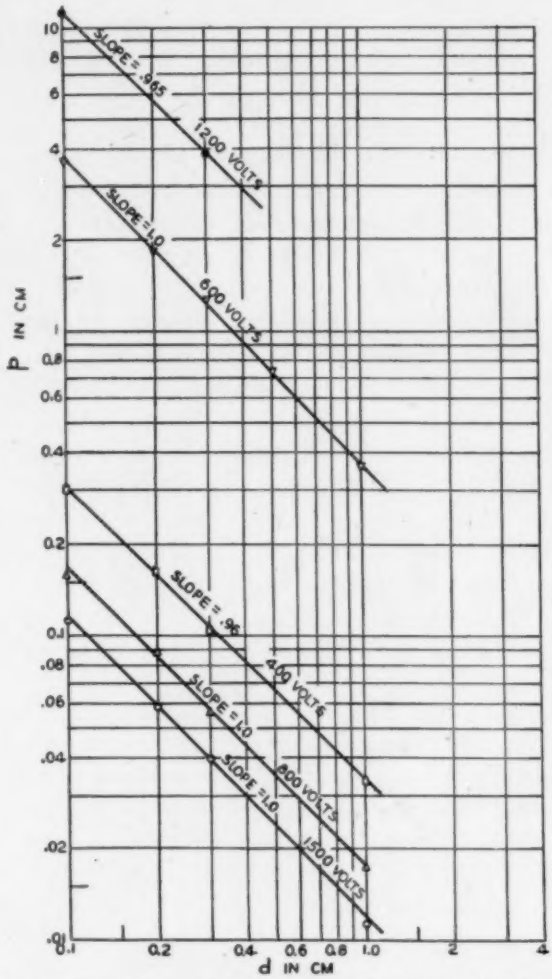

FIG. 2. Pressure *vs.* electrode separation for sparking potential of air between plane electrodes, data from Carr.

[5] Phil. Trans. **201**, 403 (1903).
[6] Zeits. f. Physik **86**, 464 (1933).

In Fig. 4, data from the experimental curves of Cobine and Power are similarly plotted, for the reignition voltages given in the legend. One notes how meager the data are for an attempt to prove so general a relation. For $V=8.1$ kv, only two points are given; a line joining them has a slope -0.93. For $V=7$ kv, three points lie on a line of slope -0.86. For $V=5.4$ kv, there are four points, only three of which lie on a line of slope -1.48. For $V=4$ kv, the four points lie on a straight line of slope -1.55. For $V=3.3$ kv only three of the four points lie on a line of slope -0.90. For $V=3$ kv, the three points do not lie on a straight line. The straight lines drawn through successive pairs of these points have slopes -2.85 and -0.92. For $V=2.5$ kv, only two points are given, and the line joining them has slope -1.65. The slopes of the different lines vary then from -0.86 to -2.85. Thus, there is a very marked difference between Fig. 4 and the preceding figures both in how well the points for constant voltage lie on a straight line and the constancy of the slopes of those lines which may be drawn. The work of Cobine and Power show that Paschen's law and the more general relation (1) do not apply for the arc reignition voltage, rather than the contrary.

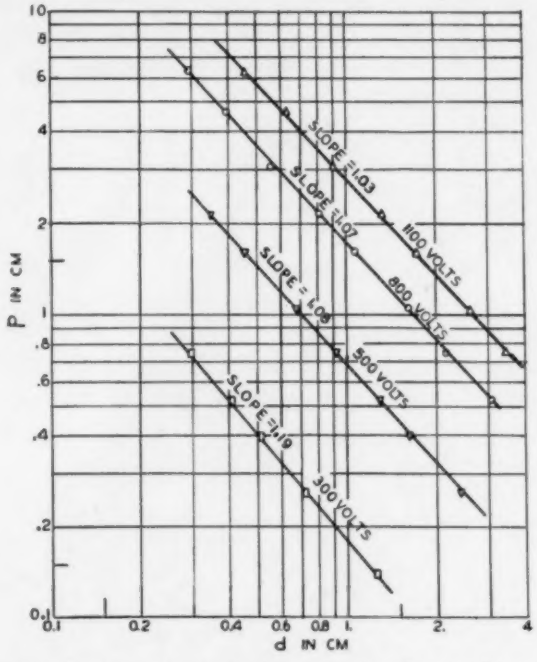

FIG. 3. Pressure *vs.* electrode separation for sparking potential of hydrogen in uniform field, data from Fricke.

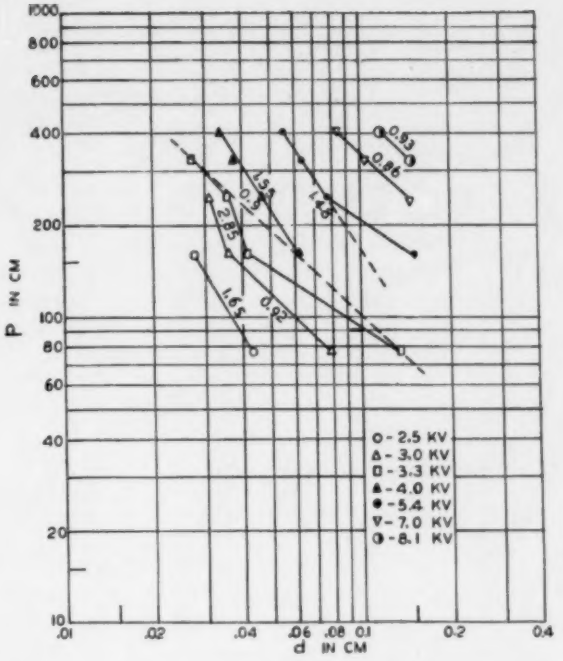

FIG. 4. Pressure *vs.* electrode separation for the reignition potential of an alternating current arc, data from Cobine and Power.

The possible processes in gas discharges which may be expected to obey the principle of similitude—a generalization of Paschen's law—have been carefully studied by Steenbeck.[7] In particular, he shows that similitude does not hold where heating effects depending on the current enter. The electric arc at high gas pressures, both in the positive column and at the electrodes, is distinguished from other types of discharges by high temperatures. On theoretical grounds then the reignition of the arc would be the very place where Paschen's law should not apply. Furthermore, the reignition of the arc probably takes place through transition from an intermediate glow. It is known experimentally that glow-arc transitions do not obey similitude relations. Finally, as Steenbeck shows, a similitude principle may be stated which holds for discharges which vary in time, provided the time scale is varied properly as p and d are varied; the relation is such that in order to test experimentally the similarity of periodically varying discharges, the frequency should be varied in proportion to the electrode separation.

[7] Wis. Veroff. a.d. Siemens-Konzern **11**, 36 (1932); also a summary may be found in v. Engel and Steenbeck, *Electrische Gasentladungen*, Vol. 2, p. 95.

A Photographic Study of the Vacuum Spark Discharge

JAMES A. CHILES, JR.
Rouss Physical Laboratory, University of Virginia, Charlottesville, Virginia
(Received July 1, 1937)

Vacuum spark discharges between electrodes of several different elements were investigated by means of a camera and high speed rotating mirror. It was found that, with very rare exceptions, the luminosity always appeared at the anode before it appeared at the cathode. Measurements were made of the time interval between the appearance of luminosity at the anode and its later appearance at the cathode, and of the velocity of the luminous vapor from the anode. Evidence is given to show that positive ions from the anode have sufficient time to cross the gap during the average observed time intervals. Hypotheses are advanced of the mechanism of the discharge and to account for the observed vapor velocities. Apparently most of the phenomena observed after the formation of vapor at the anode can be accounted for by relatively low gap potentials.

INTRODUCTION

IN 1897 R. W. Wood[1] discovered that x-rays were emitted from the anode in a vacuum spark discharge. He attributed the production of x-rays to electronic bombardment. Since that time vacuum sparks have been studied by many investigators.[2–4] From their work it has been concluded that the vacuum spark discharge is initiated by field currents from the cathode, which vaporize the anode surface by electron bombardment and thereby furnish ions for the breakdown. The purpose of the present work is to test this hypothesis and, if possible, to throw further light on the mechanism of the breakdown.

EXPERIMENTAL PROCEDURE

A diagram of the circuit is shown in Fig. 1. The vacuum gap was at G. Light from the vacuum spark was caught by the lens L_c, and after reflection from the rotating mirror M was brought to focus on the photographic plate P. The vacuum gap was oriented so that the image at P moved in a direction perpendicular to the axis of the electrodes. The mirror M was made of stellite, and was mounted on a high speed air turbine.[5] It was driven at a speed of about 1650 r.p.s., and the image was swept across the plate at a speed of about 1.5×10^6 cm/sec. The images on the plate were magnified 2.6 times.

Potential necessary to break down the vacuum gap was furnished by the Marx impulse generator shown, which could apply across the gap a potential of 120 kv. The maximum energy stored by the condensers was about 18 joules, and the maximum current was about 2000 amperes.

The circuit was tripped by means of ultraviolet light from the small brass spark gap U. When the mirror M was in the position shown, the ultraviolet light was reflected from the mirror through the quartz lens L_q, and was brought to focus on the cathode of the first-stage gap G_T of the Marx generator. Closing the switch S turned on the ultraviolet light and

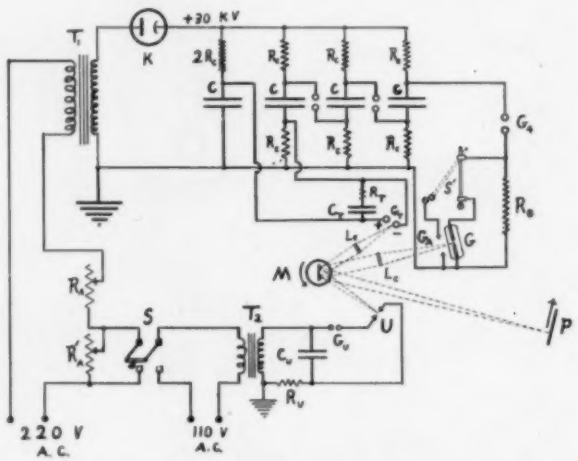

FIG. 1. Schematic diagram of apparatus showing vacuum gap G, and rotating mirror M, together with synchronizing and input circuits.

[1] Wood, Phys. Rev. **5**, 1 (1897).
[2] Hull and Burger, Phys. Rev. **21**, 1121A (1928).
[3] Snoddy, Phys. Rev. **37**, 1678A (1931).
[4] Beams, Phys. Rev. **44**, 803 (1933).
[5] Beams, R. S. I. **1**, 667 (1930); **6**, 299 (1935).

raised the potential across G_T to the proper value by cutting out the resistance R'_A. In order to avoid burning the electrodes of the vacuum gap unnecessarily while adjusting the timing, there was placed immediately in front of the vacuum tube the air gap G_A, the flash from which could be seen on a ground glass screen at P if the timing was correct. The high voltage switch S' was thrown to the dotted position while the timing was being adjusted, and was thrown to the solid position when the vacuum gap was to be connected into the circuit.

Observations with electrodes of commercial tungsten and with electrodes of aluminum, bismuth, cadmium, copper, graphite, lead, magnesium, tin, and zinc were made with the Pyrex tube shown in Fig. 2(a). The electrodes of the element under investigation were at E, held by the brass spring clips C. The adjustable rods R and the end plates P were made of brass. Light to the camera lens passed through the plate glass window W. The tube was put together with Pizein and de Khotinsky cement.

In order to study the effects of outgassing on electrodes of pure tungsten and palladium, the tube shown in Fig. 2(b) was used. Nothing but Pyrex and pure tungsten was used in its construction. The pure tungsten electrodes were at

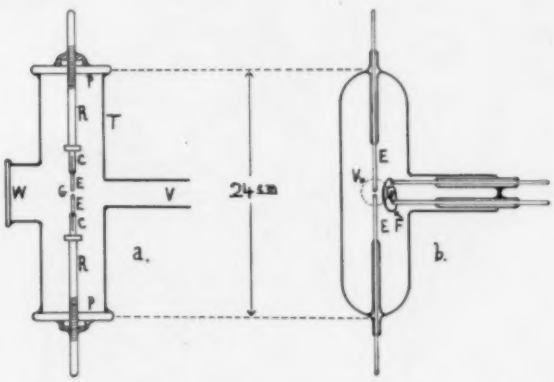

FIG. 2. a, Diagram of vacuum tube used for first ten elements in Table II. b, Diagram of vacuum tube used for pure tungsten and palladium, showing filament F for outgassing.

E. Outgassing was effected by heating by electron bombardment from the tungsten filament F. Light to the camera lens left the tube in a direction out of and perpendicular to the paper in Fig. 2(b). The tube was evacuated through the opening V on the other side. When palladium electrodes (3.0 mm long and 1.3 mm in diameter) were used, they were electrically welded to the ends of the tungsten electrodes.

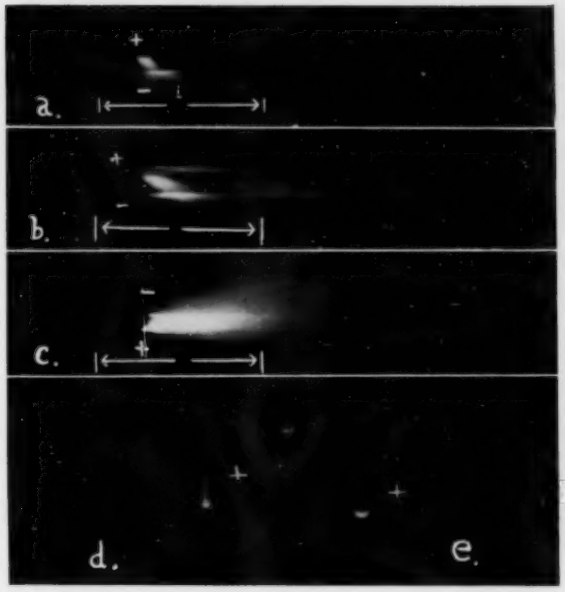

FIG. 3. a, Vacuum sparks between copper electrodes 1.15 mm in diameter, separated 0.87 mm. Potential across gap was 80 kv. b, Vacuum sparks between lead electrodes 1.6 mm in diameter, separated 1.1 mm. Potential across gap was 80 kv. c, Vacuum sparks between commercial tungsten electrodes 1.15 mm in diameter, separated 0.78 mm. Potential across gap was 95 kv. In a, b and c the images are moving from left to right. The distance between the marks indicated by arrows represents 2.0 microseconds. d, X-ray pinhole photograph of ten successive sparks between two 1.15 mm commercial tungsten electrodes separated about 0.90 mm. e, X-ray pinhole photographs of twelve successive sparks between two copper electrodes separated about 1.0 mm. The cathode was a 2.1 mm copper cylinder with a rounded end, and the anode was a 3.0 mm copper ball on the end of a 1.2 mm copper rod.

All of the electrodes used in this work were cylindrical rods with rounded ends.

The tubes were evacuated by means of a high vacuum system employing a mercury diffusion pump. A solid CO_2 trap was always maintained between the tube and system. Except when hydrogen soaked palladium electrodes were used, the pressure during runs, as indicated by a McLeod gauge, was 10^{-6} mm or less.

EXPERIMENTAL RESULTS

Figure 3, a, b, and c, shows pictures of vacuum sparks taken with the apparatus. d and e were made with an x-ray pinhole camera.

Investigations were made of vacuum sparks between electrodes of the elements listed in Table II. For each element used a series of photographs was taken with the polarity of the electrodes one way and a series with the polarity reversed (except in the case of pure tungsten). For each picture there was measured and recorded the time interval in the appearance of luminosity at the anode before its appearance at the cathode, and the velocity of the vapor from the anode.

TABLE I. *Commercial tungsten.*

Electrode Separation mm	Time Interval sec.	Vapor Velocity cm/sec.
0.78	1.9×10^{-8}	5.4×10^{5}
0.78	2.4×10^{-8}	4.6×10^{5}
0.78	1.75×10^{-8}	5.4×10^{5}
0.81	2.8×10^{-8}	5.8×10^{5}
0.81	1.3×10^{-8}	5.6×10^{5}
0.84	4.3×10^{-8}	6.15×10^{5}
0.84	2.5×10^{-8}	4.2×10^{5}
0.84	3.8×10^{-8}	5.0×10^{5}

Table I gives a typical set of data, obtained with two 1.15 mm commercial tungsten electrodes. It can be seen that the vapor velocity is much more constant than the time interval. This was found to be true in general of the other elements studied.

In Table II are given the results obtained with the elements used. Because of the large variation in the observed time intervals, the range of these as well as the average time intervals are listed for each element. In the results for the outgassed pure tungsten and palladium, the pure tungsten was outgassed $1\frac{1}{2}$–3 hours and the palladium was outgassed 2 hours.

Except in a few rare instances, luminosity always appeared at the anode before appearing at the cathode. The edges of the traces formed by vapor from the anode were straight as far as could be determined.

The images given by electrodes of bismuth, cadmium, lead, and tungsten were very dense, while those from aluminum electrodes were much lighter. There was no noticeable difference in the appearance of the images given by outgassed and un-outgassed tungsten, nor was there any appreciable difference in the images given by outgassed and hydrogen soaked palladium. The images given by graphite were so faint that the cathode hot spot was usually invisible. Only a faint trace of vapor could be seen coming from the anode.

In the case of copper electrodes, the time interval decreased progressively from 9.3×10^{-8} seconds in the first image to 2.4×10^{-8} seconds in the sixth image. The electrodes were new when the series was begun.

In one of the images obtained with tungsten there appeared on the cathode tip a fine luminous point which started 17×10^{-8} sec. before the main cathode hot spot. One or two such points also appeared in the other tungsten pictures. In the above mentioned tungsten image there also appeared a second discharge, to all appear-

TABLE II.

Element	Electrode Diameter	Electrode Separation	Range of Time Intervals	Average Time Interval	Average Vapor Velocity	Potential Applied Across Gap
	mm	mm	seconds	seconds	cm/sec.	kv
Aluminum	1.6	1.1	$1.8 - 5.9 \times 10^{-8}$	4.1×10^{-8}	7.3×10^{5}	75
Bismuth	1.5	1.0	$4.2 - 5.7 \times 10^{-8}$	4.7×10^{-8}	8.9×10^{5}	85
Cadmium	1.5	1.1	$2.9 - 5.2 \times 10^{-8}$	3.1×10^{-8}	5.4×10^{5}	80
Copper	1.15	0.89	$2.4 - 9.3 \times 10^{-8}$	5.6×10^{-8}	5.8×10^{5}	80
Graphite	2.0	1.05			2.5×10^{5}	55
Lead	1.6	1.1	$1.2 - 4.7 \times 10^{-8}$	2.9×10^{-8}	5.0×10^{5}	80
Magnesium	1.6	1.0	$1.8 - 9.1 \times 10^{-8}$	5.5×10^{-8}	7.9×10^{5}	75
Tin	1.6	1.3	$-0.91 - 2.2 \times 10^{-8}$	0.34×10^{-8}	5.4×10^{5}	80
Commercial tungsten	1.15	0.81	$1.3 - 4.3 \times 10^{-8}$	2.4×10^{-8}	5.4×10^{5}	95
Zinc	1.6	1.0	$1.9 - 3.5 \times 10^{-8}$	2.8×10^{-8}	7.3×10^{5}	80
Pure tungsten outgassed	1.3	0.60	$2.1 - 3.2 \times 10^{-8}$	2.5×10^{-8}	5.2×10^{5}	120
Pure tungsten not outgassed	1.3	0.55	$2.3 - 4.1 \times 10^{-8}$	2.8×10^{-8}	5.0×10^{5}	120
Palladium outgassed	1.3	0.95	$5.1 - 7.5 \times 10^{-8}$	5.3×10^{-8}	6.5×10^{5}	—
Palladium soaked in hydrogen	1.3	1.0	$1.3 - 6.9 \times 10^{-8}$	4.5×10^{-8}	5.0×10^{5}	—

ances identical with the first, about 44×10^{-8} sec. after the beginning of the first discharge Such second discharges were occasionally faintly discernible in other tungsten pictures. No other element studied exhibited either of these two features.

Discussion of Results

Assuming a uniform acceleration across the gap, calculations show that, under the applied potentials listed in Table II, singly ionized atoms of all the elements used could cross the gap in less than 10^{-8} seconds. Moreover, calculations indicate that, for all the elements on which experiments were made (with the exception of tin, about which more will be said later), singly ionized atoms from the anode should be able to cross the gap during the average observed time intervals under potentials as low as 160 to 6300 volts.

The observed velocities of the luminous vapor from the anode are remarkably constant for the different elements used (see Table II), ranging with the exception of graphite, from 5.0×10^5 cm/sec. to 8.9×10^5 cm/sec. These vapor velocities correspond, in the case of singly ionized atoms, to potential falls of only 0.4 to 86 volts, depending on the element. The vapor traces in the photographs from which the velocity measurements were made were quite straight, as far as could be determined, indicating no noticeable acceleration. Although the cloud of vapor undoubtedly expands in crossing the gap, the velocity of expansion is probably small compared to the component of velocity across the gap.

The observed vapor velocities could hardly be temperature velocities, since they would correspond to temperatures of around 200,000°K. Assuming a uniform field across the gap, the minimum potential required to enable a singly ionized bismuth atom to cross the gap during the average observed time displacement is 1900 volts, and that for aluminum is 410 volts. Calculations show that even under gap potentials as low as these, singly ionized bismuth and aluminum atoms from the anode could acquire the vapor velocities observed for these elements in distances of only 5×10^{-2} mm and 2×10^{-2} mm, respectively. Hence a possible explanation of the observed vapor velocities may be that the cloud of luminous vapor leaves the anode surface as ions, and that after a very short initial field acceleration these ions recombine and continue their journey across the gap, their luminosity being largely due to intense electron bombardment. Since distances of 5×10^{-2} mm are too small to be detected in the photographs, the luminous vapor traces appear to be straight clear up to the anode surface. All of the above figures give minimum voltages; it is by no means assumed that the actual gap potentials are necessarily this low.

The data obtained from these experiments are not sufficient completely to determine the mechanism of the vacuum spark discharge. However, the above considerations indicate that when the potential is first applied there is a pure electron discharge, which vaporizes the anode surface by electron bombardment and gives rise to a cloud of ions. Some of these ions then cross the gap at relatively high speed and, either by bombardment of the cathode surface or by increasing the field emission from points on it, or by a combination of both, raise the temperature of the cathode and form the cathode hot spot.

Spectrographic examinations of anodes bombarded by high speed electrons have shown that the positive ions formed by the bombardment have a high degree of ionization,[6] and it is hence probable that some of the positive ions formed during the discharge are highly ionized.

Although the data are not sufficient to show exactly when the potential falls or what the actual gap potentials are, the calculations enumerated above indicate that the phenomena observed after the formation of vapor at the anode can be accounted for by relatively low potentials of a few hundred to a few thousand volts. It is probable that the discharge has reached the arc stage by the time the cathode hot spot is formed.

The fine points of light appearing on the cathode ahead of the main discharge in some of the tungsten pictures are thought to be due to the burning off of fine points by the high field

[6] See *Baly Spectroscopy*, Vol. 2 (Longmans, 1927), p. 124.

currents through them. This seems to furnish evidence that the formation of the cathode hot spot might be due largely to the heating of fine points by high field currents, as suggested above. However, assuming physical constants about average for those of the elements used, calculations indicate that, to raise the temperature of a small projection on the cathode surface to incandescence in 4×10^{-8} sec. by I^2R heating would require several hundred times the current requisite to raise the same projection to incandescence in the same time by positive ion bombardment, even with a potential across the gap as low as 3000 volts. If the potential has fallen considerably prior to the formation of the cathode hot spot, there are probably a large number of ions in the gap at this time. Hence it would seem that the heating of the cathode surface is due more to positive ion bombardment than to increase field emission from points.

As the electrodes used were quite large in comparison to the gap separations, it is possible that the large variations in the observed time intervals were caused by the ions traveling diagonally across the gap between points formed on the electrode surfaces by preceding discharges.

In the case of tin, the observed time intervals were much smaller than those obtained for the other elements listed, the cathode hot spot often appearing before luminosity at the anode (probably due to reasons given above). (See Table II.) Assuming uniform acceleration across the gap, the potential necessary to get a singly ionized tin atom across the gap during the average observed interval of 0.34×10^{-8} seconds would be over four times the applied potential of 80 kv. However, half the applied potential could get a singly ionized tin atom across the gap in 10^{-8} seconds, which is well within the range of observed intervals for tin. Because of the inaccuracy of the measurements for such small time intervals, the average of 0.34×10^{-8} seconds obtained may easily be too small. Tin crystallizes very readily, and the field currents obtained with electrodes of this element may have been much greater than in the case of the other elements used. Since this would give rise to a larger total number of ions and hence to a greater quantity of highly ionized atoms, the small time intervals obtained with electrodes of tin may in part have been due to a relatively large number of highly ionized atoms in the gap.

The very faint images given by electrodes of graphite can probably be attributed to the high boiling point of this element, which permitted only a small quantity of vapor to be emitted from the anode surface.

In addition to the well-defined vapor traces from which the vapor velocities given in Tables I and II were measured, there was occasionally present in the photographs another very faint and indistinct vapor trace, starting from the anode at the same time and coming off at a much greater angle. The velocities given by these traces ranged from 7×10^5 cm/sec. to 30×10^5 cm/sec. They varied so much with the same pairs of electrodes that no figures for them are included in Tables I and II. They also appeared in pictures obtained with electrodes of outgassed tungsten and palladium, and therefore could hardly be due to gas adsorbed on the surface of the electrodes.

The progressive decrease in the time interval observed with copper electrodes may have been caused by progressive roughening of the cathode surface by successive discharges, which formed points increasing the field emission.

The second discharges which sometimes appeared in tungsten pictures about 4 or 5×10^{-7} seconds after the initial discharge are not thought to be due to a second oscillation, since the circuit period was 8.1×10^{-7} seconds. Apparently the arc went out and was reformed again about 4 or 5×10^{-7} second later.

In conclusion I wish to express my sincere appreciation to Professors J. W. Beams and L. B. Snoddy of this laboratory; to the former for suggesting the problem and for his assistance and direction in carrying out the work, and to the latter for his valuable assistance and advice.

Concerning the Cutting of Glass

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Glass plates were found to be more difficult to break when an interval elapsed between marking and breaking. This was associated with a decrease in the strain. Apparatus for applying uniform force in marking glass is described; also, a device for studying breaking loads. Marked samples of glass were found to break when subjected to diminished loads for appreciable intervals. A correlation was shown between the breaking load and the load on the marker.

IF photographic plates are marked with a glass cutter and then allowed to stand for some time, they are more difficult to break than similar specimens broken immediately after marking. Again, a deeply furrowed piece of glass is sometimes more difficult to break than one lightly marked. Apparently, then, an essential, primary action of the glass cutter is to produce strains which guide and facilitate breaking but decrease in magnitude with the passage of time.

Such strains in glass, marked with a diamond or steel wheel, should be evident when a specimen is examined in polarized light. Accordingly, a microscope slide, ruled almost noiselessly with a diamond, was placed with the scratch parallel to the axis of a polarizing microscope. A sensitive tint plate showed a decided blue and red pattern. A Babinet compensator, with a calibration factor about 1 millimicron retardation per division, used in conjunction with the same microscope, indicated 123 divisions. These observations, it should be pointed out, confirm and supplement some work of Rinne.[1] Five hours after the initial observation, the blue and red pattern with the sensitive tint plate had changed somewhat in character and faded to a considerable degree. The reading of the Babinet compensator had dropped to 20 divisions and a greater torque was required to break this specimen at the old mark than at a freshly made scratch. Evidently, the glass cutter produced strains which diminished considerably during this interval.[2]

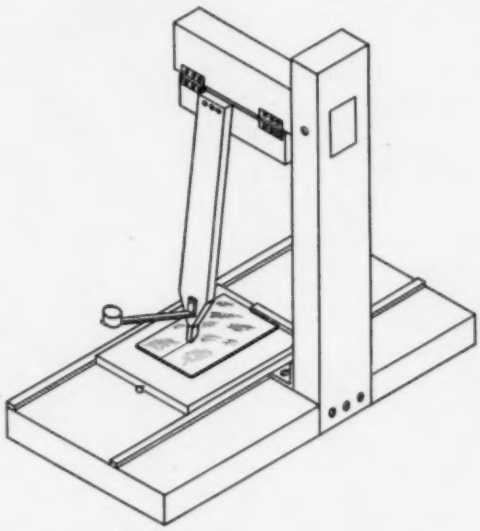

FIG. 1. Apparatus for marking glass with a moderate uniform force on the glass cutter.

DEVICES FOR MARKING AND BREAKING GLASS

Experience with cutting glass by hand had indicated that a most essential condition is the application of moderate, uniform force on the glass cutter when marking specimens. An effective apparatus for doing this is shown in Fig. 1. The head of a diamond glass cutter is fastened to a small steel rod which projects from the lower end of an upright, wooden arm, hinged, at the top, to a cross member, as shown. A metal arm, projecting to the left, is loaded as illustrated. The glass plate to be marked is held against a stop on a platform which slides between guides. While the diamond rests on the glass, the platform is moved at a uniform rate. This apparatus served admirably to eliminate uncertainty and annoyance from cutting photographic plates. Under other conditions, the same idea might advantageously be carried out in other ways,

[1] Spannungserscheinungen an Gläsern, Glastechnische Berichte **6**, 65–76 (1928).

[2] The writers wish to acknowledge their indebtedness to the Bausch and Lomb Optical Company, and particularly to their Mr. F. W. Forrest, for suggesting that a specimen be examined edgewise rather than with the surface scratched by the glass cutter flat on the stage of the polarizing microscope, and for cooperation in testing this procedure.

such as mounting the diamond or wheel under a horizontal, hinged arm, on a movable, jointed arm or above a rotating table.

The apparatus illustrated in Fig. 2 was used to determine the torque necessary to break variously treated specimens. At the right end,

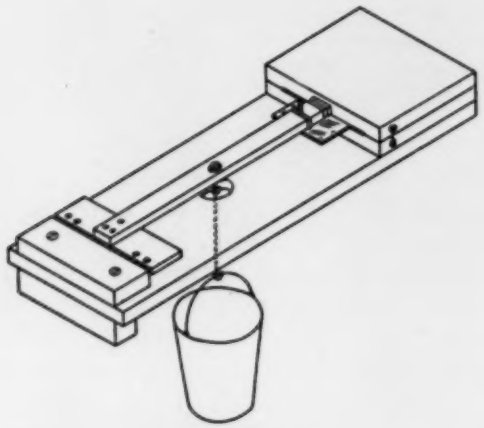

FIG. 2. Apparatus used to determine torque necessary to break specimens.

two hardwood blocks are hinged together and fastened to a wooden base. The upper block is recessed to hold a strip of glass. The glass to be broken is placed in the recess, face up, with the mark made by the glass cutter flush with the edge. The blocks are then clamped tightly together by hooks on each end. A hinged arm extends from the left. Contact with the glass is made by a rubber-covered wire wound once around a groove near the right end. A hook, near the middle of the lever arm, carries a wire which passes through a hole in the base and supports a pail into which sand is poured.

Effect of Interval Between Marking and Breaking

These devices were used to investigate the effect of the length of the interval between marking and breaking a piece of glass on the torque required for breaking. Several, similar, transverse marks were made upon each of a number of strips of glass, $\frac{7}{16}$ inches wide, cut from photographic plates. The load of sand necessary to break each strip at the first mark was determined immediately after marking. Other segments were broken off at the ends of measured intervals. Fig. 3 shows typical average data obtained under these conditions. Associated with a reduction of strain, the curve discloses about 30 percent increase in the breaking torque, during a sixteen day interval, the majority of which occurs within the first two days.

Delayed Breaking Under Reduced Loads

Another series of tests was carried out to determine the behavior of marked specimens subjected to loads smaller than those required for immediate breaking. Strips were ruled as above and the load required to break off the first segment was determined as usual except that some weights were placed in the pail before any sand was poured in. Then a predetermined weight was removed from the pail, the next mark on the strip shifted into breaking position and the loaded lever arm gently lowered into contact with the glass. The time required for the strip to break, under this lighter load was noted. Fig. 4 indicates the general trend of such data with average intervals between applying the load and breaking plotted against percent underloading. It is to be noted that glass breaks within a comparatively short time, even when bearing as little as 50 percent of the load required for immediate breaking. This suggests an element of risk in subjecting glass under strain to even small, external stresses.

The Breaking Process

The torque required to break an unmarked strip similar to those with which Fig. 3 is concerned is about 6000 centimeter grams. This is roughly five times that required to break a

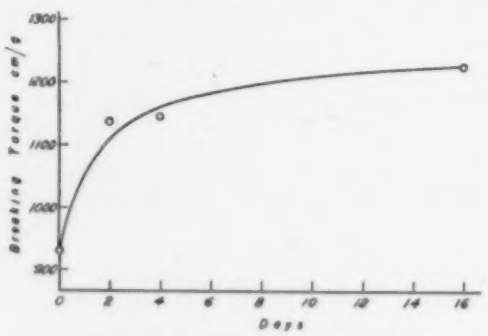

FIG. 3. Relation between breaking torque and recovery interval.

strip sixteen days after it has been marked. Perhaps three factors are involved, to greater or less degree, in the breaking process: (1) strain produced by the glass cutter, (2) abrasion of such shape that intense strain appears at its apex when external stress is applied and (3) actual splitting of the glass under the scratch. Rinne[1] points out that when a crack occurs in glass which is being heated unevenly the sides of the crack are largely free from strain, as are the fragments in cases of fracture. He adds, however, that optical evidence of intense concentration of strain at the head of the crack advances into the glass as further splitting occurs. Any strain remaining in the glass from the marking process is augmented by that due to mechanically applied stress. Where the resultant

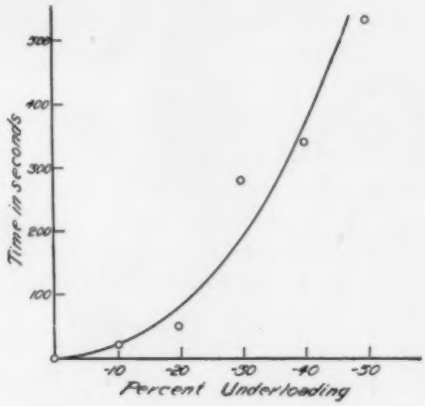

FIG. 4. Relation between the underloading required to produce a delayed breaking (in seconds) as compared with the load required for immediate breaking.

maximum intensity of strain is produced, there is a strong tendency for it to be relieved by a slight splitting. If there is initially an appreciable furrow, or as soon as any slight splitting has occurred, the applied load tends to widen it. The strain, continually appearing in maximum intensity at the apex of the advancing crack facilitates further splitting—perhaps with increasing velocity as the unbroken portion becomes thinner—until breaking is complete. With

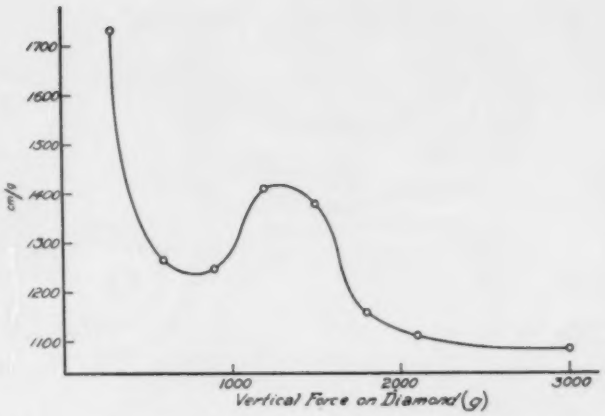

FIG. 5. Relation between the breaking torque required and the load used for marking the glass.

a full breaking load, the process is practically instantaneous but with underloading it may require considerable time.

EFFECT OF LOAD ON MARKER

Glass strips were marked when various loads were on the projecting arm of the glass cutter. The corresponding torques required to break these strips were determined. Fig. 5 illustrates a relation found to exist between breaking torque and force applied vertically on the diamond. Under light loads, increasing loads on the marker facilitate breaking. Beyond a certain value, additional loading makes breaking more difficult. Finally, with still heavier loading, the torque required for breaking decreases once more. Variations in the load on the marker affect several factors, such as the intensity and distribution of strains, the depth and shape of the furrow and the number of fragments thrown out. When considerable force is applied on the diamond, slight fractures radiate from the furrow produced. At the edge where the diamond completes the scratch, such fractures are visible under the microscope and some produce interference colors. A load on the marker which corresponds closely with the minimum in Fig. 5 proved especially satisfactory for cutting photographic plates.

An Electron Diffraction Study of the Effect of Heat upon the Structure of Gold Leaf

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(Received July 14, 1937)

The construction of an electron diffraction apparatus is described, adapted to both reflection and transmission studies of crystalline materials and built in the laboratory at a moderate cost. This apparatus involves several novel features of construction and utilizes an electrode magnet for obtaining a homogeneous beam of electrons. The application of the instrument to chemical problems is illustrated by the results of a study of the effect of heat and of various gaseous atmospheres upon the structure of gold leaf. Microscopic, x-ray and electron diffraction evidence indicate that at a temperature of about 400° the gold in a leaf flows into aggregates or larger crystal grains. This coagulation explains the contraction of the leaf as observed visually, the opacity of many patches in the heated leaf as observed microscopically, and the appearance of spots in the diffraction patterns. A "many ring" pattern observed when the leaf is heated in air or oxygen is attributed to the formation of an oxide which is rather unstable at about 400°. This observation clarifies some discrepant data in the literature.

THE method of electron diffraction applied to the analysis of structures of materials has become a necessary and complementary equipment in the laboratory in which the x-ray diffraction method is being used. It is the purpose of this paper to describe the construction of an apparatus which can be adapted to both reflection and transmission studies of crystalline materials and which can readily be assembled at a very moderate cost. The application of this instrument to a series of chemical problems will then be illustrated by the results of a study of the effect of heat and of various gaseous atmospheres upon the structure of gold leaf.

The electron diffraction instrument is constructed almost entirely of brass and is, therefore, of rugged construction. The design is as simple as is consistent with efficiency of operation. Fig. 1 shows two views of the assembled apparatus with the principal features exposed in detail to indicate their construction. The appended scale indicates the size of the principal parts.

Notes on Details of Construction of the Apparatus

A hot cathode was chosen chiefly for the sake of simplicity, since the use of a magnetic selector obviates the necessity of applying a constant high potential. The use of the filament cathode presented no problem in this respect. The primary collimator (11, Fig. 1) is turned out of a brass rod to one-half inch in diameter with a small flange at the end nearest the magnet, which serves to hold it in place. In this same end is drilled a one-sixteenth inch hole and a one-fourth inch hole is drilled up to it from the other end of the rod. A one-eighth inch sheet of iron is then soldered on to this open end by means of silver solder. A one-sixteenth inch hole is then drilled in the center of the iron plate. After polishing the iron end very thoroughly with emery a collimator is inserted in the brass tube protruding from the brass anode block, which constitutes the wall of the cathode chamber.

A primary requirement in electron diffraction is a beam of electrons of uniform and constant velocity. Such a homogeneous beam is generally obtained by smoothing the high tension current with a valve and suitable condensers. An alternative method is filtration of electrons of uniform energy out of a heterogeneous beam, either by an electrostatic field or an electromagnet. The latter is incorporated in this apparatus.

Rather arbitrarily an angle of 30 degrees was chosen for the deflection of the electron beam by the magnet. Calculations were carried out to ascertain the strength of the field required to deflect electrons of 30 kv through this angle. This energy was chosen as being representative of the electron energies to be used in subsequent work, but in winding the magnet provision was made for faster electrons. The poles of the magnet (14, Fig. 1) were constructed of soft iron, $\frac{1}{2}$ inch in diameter. When in place, the ends

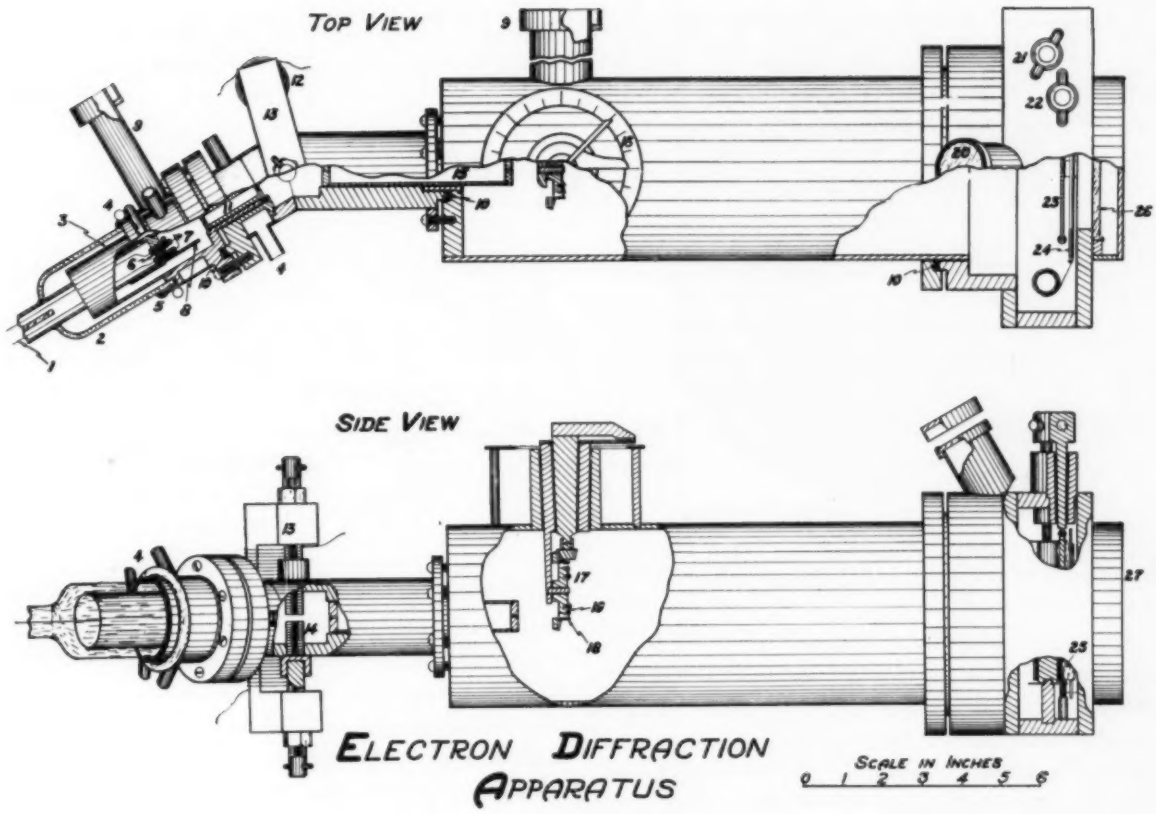


FIG. 1.

1. Filament leads
2. Glass cathode arm
3. Brass shield
4. Cooling tubes
5. Picein joints
6. Mica insulation
7. Tungsten filament
8. Iron focusing shield
9. Evacuation ports
10. Rubber gaskets
11. Primary collimator
12. Solenoid
13. Soft iron core
14. Magnet poles
15. Secondary collimator
16. Graduated scale
17. Specimen wheel
18. Specimen pinhole
19. Specimen clamp
20. Observation window
21. Film winder
22. Shutter control
23. Shutters—door-type
24. Shield defining area of photograph
25. Photographic film
26. Fluorescent observation window
27. Brass cap

of the poles are separated by $\frac{3}{16}$ inch. If a uniform field throughout the space between the poles is assumed, the radius of electron path, R, is equal to about 2.5 cm. By substitution of the proper values in the equation for magnetic deflection, $Hev = mv^2/R$, and since the electron energy is related to the potential V, by the relationship, $Ve = mv^2/2$, it is calculated that a field of about 225 gauss is sufficient; or, in the general case, $H = 1.3V$, where H is expressed in gauss and V in volts.

The solenoid (12, Fig. 1) is wound on a soft-iron U-shaped core of one square inch cross section (13, Fig. 1). A $\frac{3}{8}$-inch bolt through each end fastens the core to the magnet poles. Assuming reasonable permeability values for the soft iron, and allowing for magnetic losses, it was computed that 450 turns of No. 18 copper wire should be sufficient to supply the required field. It is desirable to use a low current in the solenoid in order to insure its uniformity. The current is supplied by a six-volt storage battery and controlled by a 30 ohm resistance in series with the solenoid. Ordinarily the current through the solenoid is about 0.15 to 0.2 ampere for electrons of the order of 30 to 40 kv. Fig. 2 shows the variation of solenoid current with the wavelength of the transmitted electrons, the latter

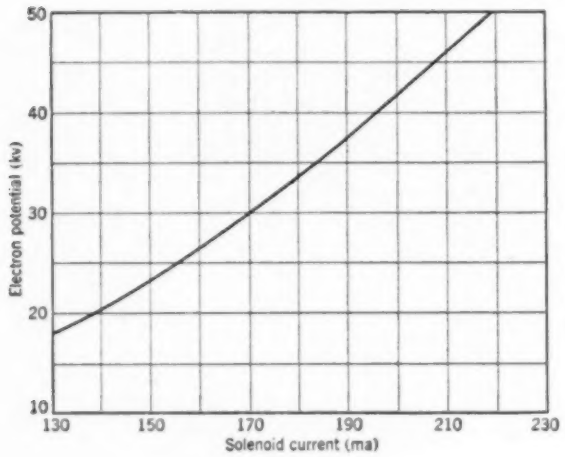


FIG. 2.

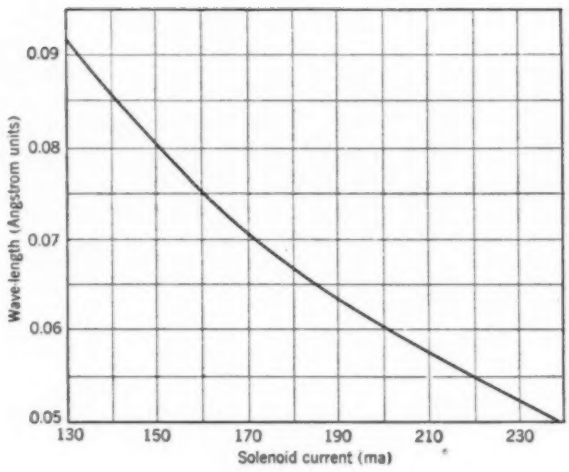


FIG. 3.

being deduced from a series of diffraction patterns of gold and zinc oxide, one serving as a check upon the other. Fig. 3 indicates the variation of solenoid current with the electron potential, the latter again calculated from the same standard patterns.

After the electrons have been spread out into a velocity spectrum, the secondary collimator (15, Fig. 1), placed in the spectrum, filters out only those electrons of a definite velocity, and therefore of a definite wave-length according to the de Broglie formula, $\lambda = h/mv$. This collimator is an iron tube $4\frac{1}{2}$ inches in length, into the ends of which are inserted the pinholes which are replaceable. Pinholes of 0.025 inch diameter in both ends are quite satisfactory. The collimator is made of soft iron to eliminate the influence of stray magnetic fields upon the electrons.

This whole section, consisting of electromagnet and secondary collimator, is conveniently attached to the specimen chamber, or main body of the apparatus, by means of a rubber gasket joint (10, Fig. 1). After assembling these parts, the secondary collimator can be moved back and forth as desired, although its exact position matters very little.

To assist in properly focusing the electron beam upon the specimen, an auxiliary, permanent magnet is placed outside of the apparatus and alongside the secondary collimator. Its position is evident from the picture of the assembled apparatus, Fig. 5, and can be varied at will.

Figure 4 shows the specimen wheel (17, Fig. 1) in more detail. Eight one-eighth inch holes are drilled in the wheel so that the center of each is in line with the electron beam as the wheel is rotated about its axis. Each hole in the wheel accommodates a pinhole specimen support. The specimen wheel has on its circumference a beveled gear which is engaged by another small beveled gear attached to the smaller tapered joint. By means of this arrangement, successive specimens can be brought into the line of the electron beam by a turn of the smaller tapered joint through an angle of 180°. The angular displacement of the tapered joints is read on a scale (16, Fig. 1) placed on top of the main tube of the apparatus. A roll film was employed because of the ease with which it can be manipulated and also because it permits taking several

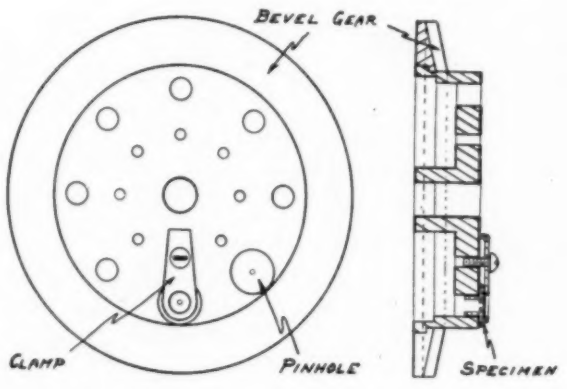


FIG. 4. Diagram of specimen wheel (17 of Fig. 1).

pictures without using a large camera chamber. We have successfully used the ordinary kodak Verichrome film, No. 118.

In order to determine the wave-length of the electrons used in producing the pattern, the diffraction pattern of a standard substance is photographed on half of the film and that of the unknown on the other half. Such a pattern is illustrated in Fig. 6. Since the latter spacing, which gives rise to a prominent ring in the standard pattern, is known the wave-length can then be calculated from a measurement of the diameter of this ring, or if a curve is plotted for the variation in ring diameter with wave-length, the latter value can be read directly from the curve. A typical reference curve of this kind is shown in Fig. 7 where the 200 and 220 diffraction rings of gold are employed as references, the one serving as a check upon the other. Similar curves have also been drawn for zinc oxide reference standard. An additional check upon wave-length is obtained by observation of the solenoid current at the time of exposure and the use of the curve in Fig. 2 to determine the wave-length of the electrons.

Use of the Electron Diffraction Apparatus in the Study of the Structure of Gold Leaf

The first problem selected for a test of the apparatus, briefly described in the preceding sections, was the peculiar effect of heat upon gold leaf.

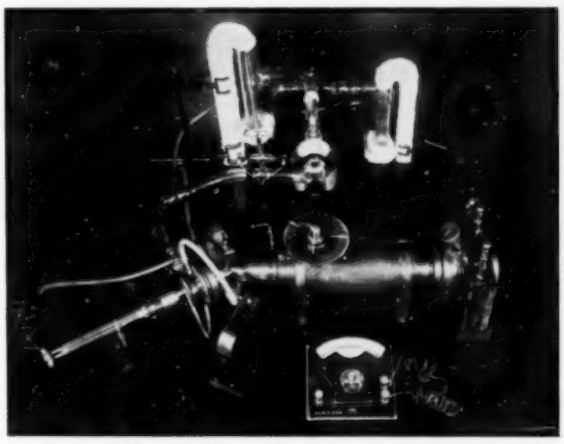


Fig. 5. Photograph of electron diffraction apparatus.

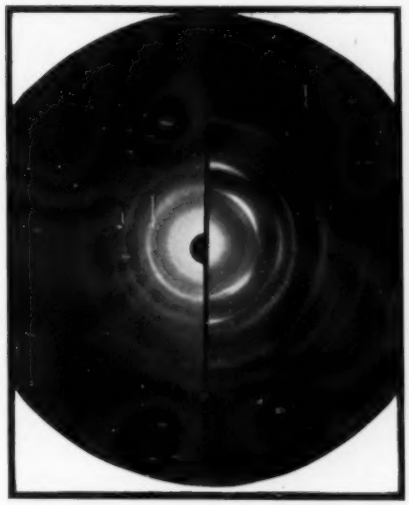


Fig. 6. Use of a standard pattern (gold) for calculation of wave-lengths of electron beam and spacings of unknown crystal.

Faraday long ago studied the visible changes in thin films of gold when these were heated.[1] He observed that heating causes not only a loss of the characteristic green color as viewed by transmitted light, but also a marked shrinkage of the leaf. This contraction was more extensively studied by Chapman and Porter[2] who determined that it begins at about 340°C. They also pointed out that this behavior is peculiar only to the very thin leaf and is not at all a property of the fine gold wire, for example. Using microscopic methods, Andrade[3] observed, in gold films heated in vacuum, what he interpreted to be a recrystallization with the (111) faces of the crystallites parallel to the substrate on which the film is placed.

The first electron diffraction studies on the effect of heat upon gold leaf were conducted by Trillat and Hirsch.[4] They reported that heating gold leaf in air causes a profound change in the diffraction pattern. They attributed the large number of new diffraction rings to the action of the air upon the gold *sans doute a une oxydation* since it is not at all produced in a vacuum. Heating in a vacuum at 400 to 500 degrees causes

[1] Faraday, Phil. Trans. Roy. Soc. 145 (1857).
[2] Chapman and Porter, Proc. Roy. Soc. **83A**, 65 (1910).
[3] Andrade, Trans. Faraday Soc. **31**, 1137 (1935).
[4] Trillat and Hirsch, J. de phys. et rad. **3**, 185 (1932); Trillat and Oketani, ibid. **8**, 59, 93 (1937).

a recrystallization and the formation of a single crystal of gold.

Although Trillat and Hirsch did not show their "oxide" pattern, there is reason to believe that it is identical with that shown by Finch, Quarrell and Wilman.[5] These investigators found that heating gold leaf in air or in oxygen produces a structure which gives rise to a pattern with bands and many additional diffraction rings. The observation that this structure could subsequently be heated in vacuum to reproduce the original pattern of gold led them to conclude that they were dealing with an interstitial entry of a gas into the gold lattice, a solid solution rather than a compound.

Recently Preston and Bircumshaw[6] also applied electron diffraction to the study of the effect of heat upon gold leaf. They found that heating in air causes spots to appear on the (220) rings of the diffraction pattern, and concluded that this is due to a crystal growth with a reorientation of the crystallites such that the (111) faces are in the plane of the leaf. They related this reorientation to the contraction of the leaf. No mention was made of the appearance of a many-ring pattern such as reported by Trillat and by Finch. They also found that heating in hydrogen and in vacuum does not produce such effects. Hence, the peculiar effect of air was tentatively explained in terms of a momentary formation, followed by an immediate decomposition, of an oxide of gold, liberating gold atoms in a new orientation.

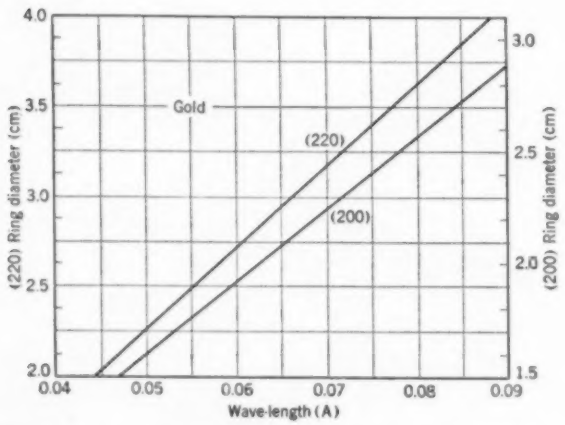


FIG. 7. Calibration of wave-lengths from (200) and (220) interferences of gold.

Swamy[7] has conducted an x-ray study of the effect of heat upon the structure of sputtered films of gold. Although he did not state the atmosphere in which it was heated, he found that heating promoted an orientation with the (111) planes parallel to the surface of deposition, and also a crystal growth. Incidentally, in comparing this observation of crystal growth with that observed by electron diffraction, one must be very cautious, for, as Quarrell[8] has pointed out, the resolving powers of x-rays and of electron beams are quite different, the latter being some hundred times that of the former.

It seems, then, that further study of the effect of heating gold leaf in various atmospheres is desirable, particularly with a view to proving the existence or nonexistence of an entry of gas into the gold lattice.

EXPERIMENTAL

The gold leaf used in our experiments was the thinnest commercially available. The small piece of leaf was mounted on a clean platinum support, $\frac{1}{4}$ inch square, and over a one millimeter hole in the center of the support. Before treating it, the gold leaf was examined with a microscope to make sure the film which covered the hole in the support was a smooth one, free from wrinkles and double layers. The film was adequately fixed in position by folding its corners over the edges of the support. The mounted leaf was then placed in a clean porcelain boat which was suspended in the center of a heating chamber. The latter was made of a two-inch Pyrex tube, eighteen inches in length. One end of the tube was provided with an inlet and outlet, each of which could be closed with a stopcock. These were used to change the atmosphere in which the gold was heated. Into the other end of the heating chamber was inserted a thermocouple of such length that the couple reached to the gold leaf. The couple was made of alumel and chromel-*P* wires, and the pyrometer was calibrated against the melting point of potassium dichromate. The heating of the chamber was effected

[5] Finch, Quarrell and Wilman, Trans. Faraday Soc. **31**, 1051 (1935).
[6] Preston and Bircumshaw, Phil. Mag. **21**, 713 (1936).
[7] Swamy, Proc. Phys. Soc. (London) **46**, 739 (1934).
[8] Quarrell, Trans. Faraday Soc. **31**, 1144 (1935).

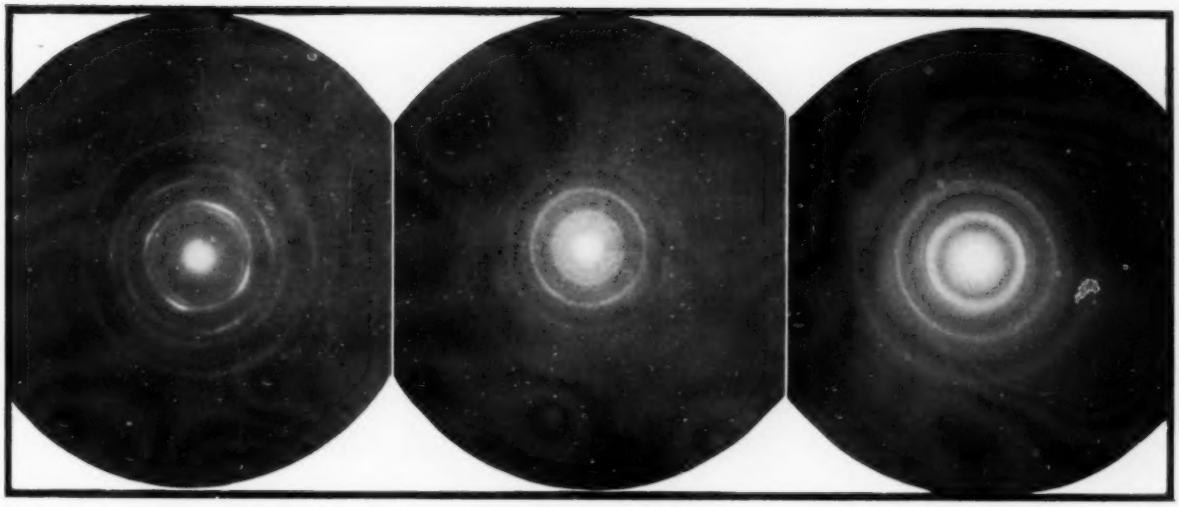


FIG. 8. Electron diffraction pattern for commercial gold leaf untreated.

FIG. 9. Pattern for gold leaf thinned with KCN.

FIG. 10. "Many-ring" pattern for gold leaf heated in air or oxygen.

by means of a burner whose flame was spread out to insure uniform heating over the area occupied by the porcelain boat containing the gold specimens.

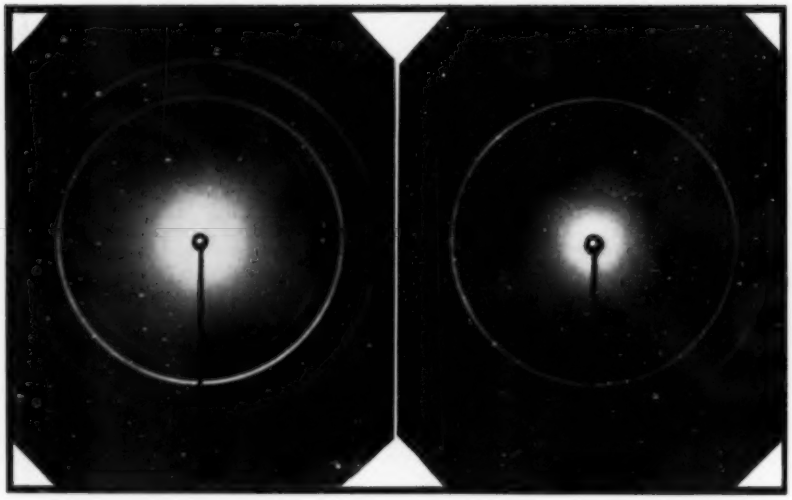
The gases which were introduced into the heating chamber were obtained from tanks. The nitrogen and hydrogen were freed from traces of oxygen by passage through a pyrogallol solution and over hot copper turnings. All the gases were finally dried with concentrated sulfuric acid. Evacuation of the heating chamber, when desired, was accomplished with a good Hyvac pump.

The leaf as it is available commercially is thin enough to transmit electrons of 30 kv or higher energy. (Fig. 8.) However, the pattern is characterized by a decided fogging. Undoubtedly this is due to the relatively great thickness of the leaf which gives rise to considerable multiple scattering. The same specimen, when thinned with a potassium cyanide solution produces a pattern relatively free from such general scattering effects. (Fig. 9.)

In interpreting an electron diffraction pattern, one must remember that the wave-length of the electrons is very small, and consequently the Bragg diffraction angle is only of the order of about one degree. Hence, a series of crystal planes must be nearly parallel to the electron beam if they are to diffract the beam and register their interplanar spacing. Fig. 8 shows that the crystallites of gold are arranged with their cube faces more or less parallel to the plane of the leaf as is indicated by the greater intensity of the (200) and (220) in comparison with the (111) and (311) rings. A perfectly fibered specimen would have all the crystallites arranged with cube faces in the plane of the leaf, and then the (111) and (311) interferences would not be registered at all. For such a specimen, the fiber axis is normal to the leaf surface and the orientation about this axis is random. The fact that the (111) and (311) rings show up faintly indicates that the fibering is by no means perfect, and some of the crystallites have no cube face in the plane of the leaf.

In this pattern it must be observed, however, that the (200) and (220) rings are broken up into arcs. These arcs are indicative of a preferential orientation of the crystallites about the fiber axis. The length of the arcs indicates a departure from the mean orientation of about ten to twenty degrees.

Naturally, this property of the untreated gold leaf to show considerable orientation not only in one, but in two directions is to be ascribed to the treatment such as rolling and beating which it has received during its preparation or manufacture. It should be mentioned here that patterns obtained by transmission through different areas of the same leaf vary greatly with respect to the degree of orientation. Therefore, care



(a) (b)

FIG. 11. X-ray diffraction patterns for gold leaf (a) before and (b) after heating in air.

must be exercised in attributing any observed orientation in treated gold leaf to the treatment, such as heating, given to it.

In the subsequent study of the effect of heat upon the structure of gold leaf, we have employed an unheated leaf as a standard for the determination of the wave-length of the electrons used. This is warranted because the size of the unit cell of gold is very well known from x-ray data. The standard specimen was a gold leaf thinned by potassium cyanide solution and washed in water and acetone. This specimen gave the pattern of Fig. 9. It indicates a nearly perfectly-fibered structure, since the (111) and (311) rings are almost entirely subdued and the other rings are free from arcs. In employing it as a standard, the (200) and (220) rings are used as a check upon each other in the determination of the wave-length of the electron beam.

OBSERVATIONS ON THE EFFECT OF HEAT UPON GOLD LEAF IN VARIOUS ATMOSPHERES

Before heating, the gold leaf appears green by transmitted light. After heating in air at 400–450° for five minutes or more the green color disappears and a colorless film with many black spots remains. The heating causes considerable shrinkage of the leaf, which also seems to become quite porous and fragile. To determine the effect of temperature, various specimens were heated in air for five minutes at the temperatures, 365, 410 and 450 degrees. The effect of the time of heating at 400° was also investigated, and it was found that the conversion to the structure giving the pattern of many rings (see Fig. 10) is complete in about fifteen minutes. Furthermore, heating in air at 350–375° for three hours was found to produce no further change. Apparently the change is a slow one at temperatures from 350 to 400° and can be accelerated by raising the temperature to about 450°.

When the gold leaf was similarly treated in a nitrogen atmosphere, a contraction occurred but the electron diffraction pattern remained unchanged. At first, when the tank nitrogen was passed only through a pyrogallol solution for the removal of traces of oxygen, a change in the diffraction pattern was observed. The new pattern was identical with that produced when the heating was carried out in air. However, when the nitrogen was more carefully purified, the gold structure showed no signs of such change. Obviously, the gold leaf at 400° or over is very sensitive to minute quantities of oxygen. Heating in an oxygen atmosphere had the same effect as heating air.

Using temperatures up to 450° and the atmospheres, hydrogen and carbon dioxide, no change in the resulting electron diffraction patterns was observed except an increase in general fogging. In both cases the leaf became darker in spots, the dark patches being separated by light cracks, but in no cases was any transparent material visible under the microscope.

An interesting and important change was observed when a specimen previously heated in air (to produce the "many-ring" pattern) was then heated in vacuum at 400° for eight hours. There is a return to the original gold structure, although the (200) ring is somewhat broken and irregular.

In summary, then, we find that heating in any of the atmospheres used produces a marked

contraction of the gold leaf and dark patches of microscopic size. On the other hand, heating in air or oxygen also causes the formation of a thin, transparent substance and the appearance of a "many-ring" diffraction pattern. Apparently the transparent material must be associated with the change in pattern.

Several gold leaves were also examined by the x-ray diffraction method, with copper radiation from a Philips Metalix tube operating at 26 kv and 20 ma, with a distance of three centimeters from specimen to film. The gold leaf was sufficiently thick to register an x-ray pattern. Fig. 11a is the x-ray photograph of an ordinary, untreated gold leaf. This same leaf when heated to 450° for fifteen minutes (these conditions give rise to the "many-ring" electron diffraction pattern) produced the x-ray pattern of Fig. 11b, which differs from Fig. 11a only in showing grain growth.

Discussion of the Results

In spite of many attempts, we have not been able to duplicate the results reported by Preston and Bircumshaw who detected spots on the (220) ring of the pattern given by a leaf heated in air to about 400° or over. They explained their observation in terms of a reorientation and a recrystallization into larger grains, the former involving a change from the (100) to the (111) planes parallel to the surface of the leaf.

Table I.

Spacings in Angstrom Units	Relative Intensities	Spacings in Angstrom Units	Relative Intensities
4.52	Weak	1.27	Moderate
2.79	Weak	1.18	Moderate
2.56	Strong	1.12	Weak
2.35	Strong	1.03	Moderate
2.05	Moderate	0.95	Weak
1.90	Moderate	.91	Moderate
1.60	Weak	.85	Moderate
1.52	Weak	.78	Weak
1.42	Strong	.70	Weak

It seems quite reasonable that the spots in the x-ray pattern for heated gold leaf are produced by the grains which appear as dark patches under the microscope. Apparently there is considerable mobility in a thin gold leaf to permit this growth in a direction normal to the surface of the leaf. It appears certain that this change is independent of the atmosphere in which the leaf is heated. The change can be likened to a "coagulation" of gold at various points, thus leaving open spots and cracks between the observed dark patches or aggregates. Such an explanation is in agreement with the observations of Andrade who noticed that heating gold films in a vacuum caused the formation of centers of crystallization, thicker than the surrounding material and therefore containing matter which was originally spread over the surrounding area.

There still remains the task of explaining the "many-ring" pattern in Fig. 10, obtained only when the leaf is heated in air or in oxygen. Accurate measurement of the spacings shows that the pattern is a very definite one, and readily reproduced. The average spacings, with their relative intensities, are listed in Table I.

The possibility suggested itself that oxygen might merely catalyze a change in the crystal structure of the gold itself. Several metals show different crystal structures at different temperatures. However, this possibility is ruled out here because the x-ray patterns for gold leaf before and after heating show the same face-centered cubic structure, indicating that at least most of the gold lattice is unchanged in the heating process.

The fact that heating in vacuum of a specimen previously heated in air (to give the "many-ring" pattern) causes a return to the original gold structure, indicates that the oxygen enters the lattice in some way or other, very likely only superficially. It appears probable that the oxygen penetrates only the surface layers of the larger gold grains, and perhaps permeates the whole of the thinnest portions of the leaf to produce the transparent material between the grains. The question still remains just in what arrangement, if any, these oxygen atoms are posited in the gold lattice.

The suggestion of Finch and his associates that the oxygen exists in the gold in solid solution is supported by the fact that it can be removed under vacuum at an elevated temperature. The bands observed in their patterns do indicate an expansion of the gold lattice, perhaps due to

the entry of oxygen. However, as Thomson[9] has pointed out, the well-defined diffraction rings which characterize the "many-ring" pattern cannot be attributed merely to a solution, but point unmistakably to a definite crystal structure, or a definite compound. By implication, Finch, Quarrell and Wilman also refute their own theory of solution when they say, "In the case of the entry of oxygen into a cubic lattice, it appears from the dimensions of the bands and 'extra' rings that the oxygen atoms enter the lattice across a cube edge, to take up the body-centered site in a face-centered cubic structure and a face-centered position in a body-centered cube."[10] Certainly such an arrangement constitutes a definite crystal structure.

Apparently, however, there is considerable hesitancy in admitting the formation of a gold oxide at the temperatures we used. Cosslett[11] has suggested that gold may be analogous to indium in its reluctance to form an oxide. He found that a very thin film of indium was easily oxidized in air at room temperature to In_2O_3, although indium does not ordinarily oxidize with such rapidity. It is very probable that the metal in a very thin film is much more porous and reactive than in the bulk or massive state. Since indium, in this condition forms an oxide so readily at room temperature, it would not be surprising if gold behaved similarly at an elevated temperature.

The evidence points to the conclusion that an oxide of gold is formed when gold leaf is heated in air to about 400°. Apparently at this temperature the gold is activated sufficiently to combine with oxygen, but an equilibrium exists which is shifted in the direction of the individual substances by prolonged heating in vacuum. The crystal structure of this oxide is probably hexagonal. The spacings in Table I cannot be harmonized with the suggestion of Finch and his associates who postulate an entrance of the oxygen atoms in the body-centered positions.

Summary and Conclusions

Microscopic and x-ray and electron diffraction evidence indicate that at a temperature of about 400°, the gold in gold leaf flows into aggregates or larger crystal grains. This "coagulation" explains the contraction of the leaf as observed visually, the opacity of many patches in the heated leaf as observed microscopically, and the appearance of spots in the diffraction patterns. Furthermore, the "many-ring" pattern observed when the leaf is heated in air or oxygen can be attributed to the formation of an oxide which is rather unstable at about 400°. The oxide theory is favored over the solution theory because of the distinctiveness of the pattern and the sharpness of the diffraction rings.

[9] Thomson, Trans. Faraday Soc. **31**, 1107 (1935).
[10] Finch, Quarrell and Wilman, Trans. Faraday Soc. **31**, 1075 (1935).
[11] Cosslett, Trans. Faraday Soc. **31**, 1112 (1935).

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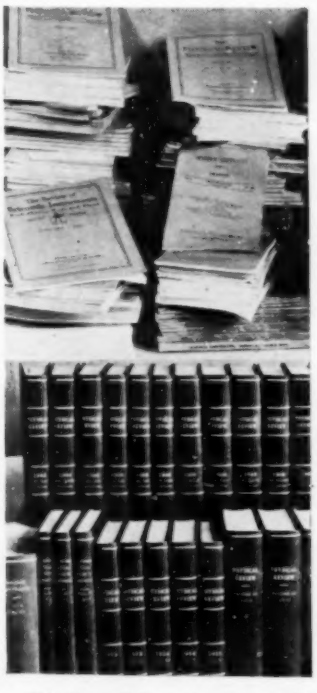

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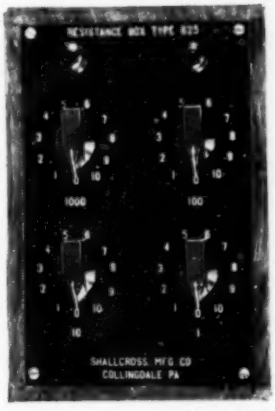

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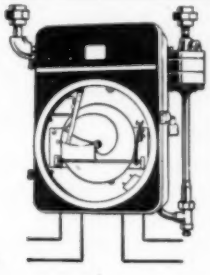

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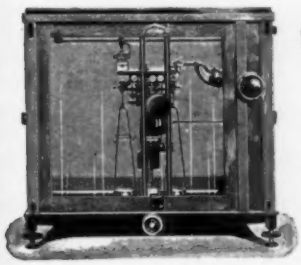

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